CARBON/GRAPHITE COMPOSITE MATERIAL STUDY

THIRD ANNUAL REPORT 1980

Office of Science and Technology Policy
Executive Office of the President

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I

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II

CONTENTS

I. PREFACE

Technically, the term "carbon fiber" is applied correctly to fibers that have been pyrolyzed at temperatures of 1100° C to 1200° C and consist essentially of amorphous carbon networks. The term "graphite fiber" is applied to carbon fibers that have been heat treated at temperatures on the order of 2200° C to 2700° C, resulting in a crystalline fiber structure. For our purposes the two terms are used interchangeably, since the characteristics under consideration are generally common to both.

The history of carbon fibers and filaments extends back to the late 1800's. Edison, in his classic work on the incandescent lamp, made carbon filaments around 1880 by carbonizing natural cellulose fibers, such as cotton and linen. Eli Whitney patented a process in 1909 for coating carbon fibers from cellulose with pyrolytic graphite by flashing at temperatures up to 4000° C. After the introduction of tungsten filaments, however, interest in carbon for lamp applications declined.

In the 1950's, the search for new materials for structural composites generated an upsurge of interest in carbon fibers. Early work at this time on pyrolyzed viscose rayon produced relatively strong flexible fibers by stretching them during carbonization at 2000° C. Although the process for producing high strength fibers was not very reproducible, reliable low-strength carbon and graphite yarns and fabrics could be manufactured. These low-strength fibers found application in tape configurations for strategic missile reentry vehicle heat shields and rocket nozzles in the early 1960's.

One of the most significant breakthroughs in carbon fiber technology occurred during 1963-1965 when it was discovered that by subjecting the precursor fiber to a rigidly controlled continuous tensile stress during the high-temperature treatment very high strength carbon filaments could be obtained; it is the high values of the specific modulus and specific strength that make these new carbon fibers very useful and desirable materials as structural reinforcing agents.

Commercial carbon and graphite fibers are made from any carbonaceous, fibrous, raw material that pyrolyzes to a char, does not melt, and leaves a high carbon residue. The physical properties of the final carbon fiber materials are extremely sensitive not only to the type of precursor material, but also to such manufacturing variables as rates of heating, maximum baking temperature, time at maximum baking temperature, the baking environment, and the strain applied to the fiber during pyrolysis. Very high modulus (or elasticity) graphite fibers in the form of continuous yarn have been developed through the application of stress to a carbon fiber yarn during heat treatment at temperatures

exceeding 2200° C. This procedure creates a more ordered microstructure in the fiber leading to a tenfold increase in the elastic modulus and a simultaneous increase in the electrical and thermal conductivity in the direction of the fiber axis.

The starting material, called the precursor, for carbon fibers is usually continuous and may be a single fiber or a multistrand filament. Prior to 1973, most major U.S. producers of carbon fibers preferred rayon precursors; however, by 1976, most major producers in the U.S. and abroad preferred a polyacrylonitrile (PAN) precursor. Production of carbon and graphite fibers from a low cost pitch or tar precursor has recently received considerable attention.

The outstanding mechanical properties of carbon fibers only become of practical interest when they can be efficiently translated into a viable structural form, such as a composite. Considerable efforts have gone into developing compatible matrix materials, composite manufacturing methods, and optimizing materials design configurations. The present generation of carbon fiber composites has unique combinations of properties which result in a significant capability for reduction in structural weight of both aerospace and transportation systems. Moreover, these same properties make possible marked economies in certain industrial operations with accompanying increases in safety for both static and rotating machinery. These composites are already providing entirely new consumer products in the areas of sporting goods, medical equipment, electronic components, etc.

National energy reduction goals and the economics associated with lower weights and reduced maintenance of transportation vehicles portend extensive future utilization of these composites. Indications are that extensive utilization of carbon fiber composites in the next generation of transportation systems will provide dramatic benefits in the form of either reduced weight, size, and cost or in improved performance, e.g., more efficient structure/lighter weight (higher specific stiffness and strength), greater ability to dynamically tailor the structure, greater ability/flexibility relative to advanced geometric shapes and structural concepts, improved fatigue characteristics, greater damage tolerance, and in the life cycle area, improved performance, reduced maintenance, improved repairability, and inherent corrosion resistance.

Commercial aircraft have begun to use carbon fiber composites and are expected to use more significant amounts of these materials with the introduction of the next generation of new or derivative aircraft. Weight reductions made possible in commercial aircraft are expected to be realized in improved fuel economy. The potential for full fleet fuel savings of some 200 million gallons of gasoline per year projected on the basis of the quantities of graphite composites expected to be used in commercial transports by 1990 is well within reach.

The Federal automobile average fuel economy standards may well cause the automobile industry to be the largest user of carbon/graphite fiber by 1990. In this time period, the U.S. automotive industry alone may use more than 1000 times the volume of graphite fiber used by the nonmilitary aerospace industry. Use of graphite composites in automobiles could result in full fleet fuel savings of as much as 2 billion gallons of gasoline per year based on the projected estimates for graphite usage in the 1990 automobile. Should the automotive industry substitute even a relatively modest amount of graphite composites for structural steel this will not only reduce the cost of graphite fibers, but sufficiently enhance the technology base so that the trucking industry likely will apply composites to new trucks. This could result in an approximate 15 percent increase in either fuel economy or load capacity. Likewise, the rail freight industry may well apply composites in an amount which could result in an increase in rail freight capacity.

Future projections indicate that as the price of carbon fibers decreases, there will be an increase in other industrial uses of carbon fiber composites due to weight and cost savings as well as to increased safety. Also, the reduced cost will lead to a rapid expansion of use by the general public in the form of sporting and household goods and other recreational articles, due to the increased performance capability that carbon fiber products can offer to the consumer.

While the potential benefits of using composites are manifold, they are not realized without some risk. A rapidly escalating usage of carbon/graphite fiber composites was predicted for aircraft, automobiles, and other applications. This created the possibility of accidentally releasing these fibers into the environment should the matrix material be burned during an aircraft crash or automobile collision. It was recognized that carbon/graphite fibers were both electrically conductive and readily propagated in air currents.

In a letter the Deputy Secretary of Defense and the Administrator, National Aeronautics and Space Administration, so advised the President of these concerns and recommended a study led by the White House. Early in their experimental applications NASA and DOD recognized that the raw fibers, if inadvertently released into the atmosphere, could pose a potential hazard to electrical and electronic equipment as well as affecting a variety of environmental conditions.

The President directed the Office of Science and Technology Policy (OSTP) to review these matters and recommend an action plan. OSTP formed an interdepartment/interagency committee to prepare a report and develop the action plan. The plan, approved by the President, was published in January 1978 (OSTP ref. 1). It identified the significant areas requiring study and assigned agencies to accomplish these studies.

This Third Annual Report is particularly significant in that it contains the final conclusions of three of the agencies involved in assessing the vulnerabilities and risks perceived to be associated with increased usages of carbon fiber composites. In this regard the NASA, DOE, and DOT have finished their tests and experiments. They have concluded their work concerning the study and their responsibilities are terminated effective with the publication of this report except as noted in Section V. The DOD has also finished its work in this program as it relates to the national tasking.

II. AGENCIES PARTICIPATING IN NATIONAL PROGRAM AND THEIR RESPONSIBILITIES

Office of Science and Technology Policy (OSTP)

Program direction

National Aeronautics and Space Administration (NASA)

Risk assessment for civil aircraft accidents
Protection measures for commercial aircraft
Alternate and modified materials
Management support to OSTP

Department of Transportation (DOT)

Risk assessment for surface transportation accidents
Protection measures for surface transportation equipment
Aircraft accident reporting

Department of Energy (DOE)

Power generation vulnerability and protection
Power transmission vulnerability and protection

Department of Commerce (DOC)

Communication and computer vulnerability and protection
Household equipment vulnerability and protection
Carbon fiber market, production, and cost analysis

Environmental Protection Agency (EPA)

Techniques for source and ambient air monitoring
Carbon fiber disposal methods

Department of Health and Human Services (DHHS)

Environmental health analysis

Department of Labor (DOL)

Industrial worker safety standards

Federal Emergency Management Agency (FEMA)

Emergency procedures
Carbon fiber incident analysis

Department of State (DOS)

International advisories
Foreign activities

Department of Defense (DOD)

Assist other agencies

Office of Management and Budget (OMB)

Funding

(A list of current representatives to the interagency committee is given in appendix A.)

III. AGENCY PROGRAM ACTIVITIES

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION (NASA)

The National Aeronautics and Space Administration tasked its Langley Research Center with the responsibility for quantifying the public risk association with the accidental release of carbon fibers from civil aircraft and for assessing the need for protection of civil aircraft systems from such fibers. This responsibility at Langley was assigned to the Graphite Fibers Risk Analysis Program Office which sponsored and coordinated 19 studies conducted by NASA centers, private contractors, and other government agencies. Individual study results are contained in some 50 NASA Technical Memorandums, NASA contractor reports, and other agency reports.

The studies focused in the areas of fiber sources, fiber transport, vulnerability of equipment and shock hazards, facility surveys, and risk assessments. They detailed a comprehensive evaluation of the potential impact of carbon fibers accidentally released in the atmosphere on electrical equipment and the potential risk to the nation from resulting failures. A major excerpt from the NASA final report is included as appendix B.

NASA also initiated an investigation of alternate materials that might alleviate the perceived risk of using carbon fibers. As the basic study progressed, however, the overall risk was shown to be orders of magnitude less than was originally thought. Therefore, the investigation of alternate materials was curtailed. The concluding report concerning this subject is found as appendix C.

Fiber Source

At the time that the study was initiated, very few carbon composite parts of civil aircraft were scheduled for series production, but extensive growth in commercial aircraft usage was anticipated. Therefore, a two-part projection of the future use of carbon composites was developed. The first part for the commercial fleet was based on the plans and capabilities of the major commercial aircraft manufacturers in the United States and the Federal Aviation Administration study of the growth of the air-transport fleet over the next 15 years. By 1993, 73 percent of the commercial fleet may be expected to contain some carbon composites. The second projection for general aviation aircraft, which includes the remainder of civil aircraft, assumed that carbon fiber usage would grow 30 percent per year from a base starting from both ongoing and planned carbon fiber applications. This assumption led to an estimate that 25 percent of the general aviation aircraft would have some carbon composite structure by 1993.

From a projection of aircraft use of carbon composites, the amount of carbon composite involved in aircraft crash fires was estimated. National Transportation Safety

Board (NTSB) records were analyzed and the consequence of accidents was assessed by a detailed review of company records of commercial airframe manufacturers. The annual rate of crash fire accidents with civil aircraft was assumed to remain constant in the future; that is, the effect of the expected expansion of the total civil fleet was assumed to be just balanced by improvements in safety.

The release of carbon fibers from burning carbon composites was quantified in nearly 300 experiments. The number of single fibers released was found to be relatively low, usually less than 1 percent of the fiber mass available in the consumed composite unless the burning debris was disturbed by explosive force. The released fibers were found to be relatively short, about 2 to 3 millimeters.

Fiber Transport

Carbon fibers released from burning composites are carried by the fire plume and dispersed downwind. The level of exposure to carbon fibers at any locality near an accident is a function of a number of atmospheric variables. For the risk analysis, existing dissemination models, which had been derived from those used by the Environmental Protection Agency, were found to be acceptable for defining carbon fiber dispersion from fires.

An airborne fiber is potentially capable of causing an electrical malfunction. However, no further hazard exists once the fiber is on the ground unless it is picked up by air currents and redisseminated in the atmosphere. A study of a site where carbon fibers had been deposited in substantial quantities 3 years earlier showed that less than 1 percent of the originally deposited fibers were redisseminated and that the redisseminated fibers were usually broken into shorter lengths. Because of these low redissemination rates, the small surface area in the country that is conducive to redissemination, and the low damage that can be done by short fibers, redissemination contributes very little to the potential risk. Therefore, in the risk analysis no redissemination was assumed.

Outdoor electrical equipment, such as power distribution lines, receives direct exposure to the disseminated carbon fibers. However, the exposure of enclosed equipment is very much lower because buildings and other enclosures provide effective filtration. For example, a carbon fiber cloud passing through a common window screen retains only one-tenth of its fibers. Nine-tenths are thus effectively blocked by the screen. The actual interior exposure is usually one or two orders less than outdoor exposure because of fiber fallout and air circulation. The fiber filtration factors used in the risk assessment were based on data from filter tests, building surveys, and correlation with air-conditioning and electrical industry standards.

Vulnerability of Equipment and Shock Hazard

Tests have shown that under certain conditions carbon fibers can cause malfunctions and damage electrical and electronic equipment. To determine the vulnerability of representative equipment, approximately 150 individual items were tested. The items selected for the tests included household appliances, business and factory equipment, aircraft avionics, and generic electrical and electronic devices. Most items, including many items found in the home, were not damaged by exposure to carbon fibers. Some, particularly fan-cooled equipment and equipment with open electrical conductors, failed, but only at carbon fiber exposure levels that would rarely be expected to occur outdoors from the burning of an aircraft using carbon composites. For the broad range of equipment considered in the risk analysis, the level of vulnerability of a particular piece of equipment was assumed to be that found in the test program for equipment of generically similar construction and circuitry.

As part of the vulnerability testing, the potential for shock hazards in electrical equipment was examined. At extreme exposure levels, some household appliances, particularly toasters, were susceptible to carbon-fiber-induced short circuits to the external case. On the basis of the test data, the projected carbon fiber usage, and the accident rate projected for 1993, analysis indicated that less than one shock annually would result from released carbon fibers. The shock current would not be lethal because the fiber would burn out before a dangerous level was reached. Therefore, the potential shock hazard is not considered a threat to life and was not considered further in the risk analysis.

Detailed analyses have been made by three domestic commercial aircraft manufacturers to evaluate the susceptibility of the civil transport aircraft to carbon fibers released in aircraft fires. The analyses were based on avionics vulnerability test data, airflow inside the aircraft (for fiber transport analysis), and the various operational modes of the aircraft. The analysis showed that for aircraft on the ground at an airport exposed to a carbon composite crash fire, the avionics equipment failure rate from the carbon fibers would be 0.0003 percent of the current normal operational failure rate.

Aircraft in flight, or in the process of landing and taking off, are considered completely invulnerable to airborne carbon fibers. Because the number of expected failures from carbon fibers is so low and because the equipment is already redundant to meet current operational requirements, no specific protection from carbon fibers is required for civil aircraft avionics. Aircraft avionics systems of the future are anticipated to be even less vulnerable to carbon fibers than the current systems because of the trends toward lower power systems with either coated circuit boards or totally enclosed cases.

Demonstration Tests

Two series of aircraft fuel fire tests were conducted which verified laboratory tests. Components of aircraft composite structure were burned in large outdoor jet-fuel pool fires to demonstrate the release and dissemination of fibers. The results indicated that less than 0.6 percent of the available carbon fiber was released into the atmosphere as single fibers. In pool-fire tests conducted in an enclosed facility, the amount of fibers released was less than 0.75 percent even when the burning composites were mechanically agitated. Exposure tests in this facility also demonstrated that the vulnerability of electronic equipment to fire-released fibers was predicted correctly by laboratory tests with virgin fibers.

Facility Surveys

Surveys were conducted to gather the data required to assess the economic impact of electrical incidents attributable to fire-released fibers. Over 60 public, utility, commercial, and industrial installations were visited to gather data on:

- The sensitivity of life-critical or emergency services to airborne carbon fibers
- The sensitivity of commercial and industrial equipment to airborne carbon fibers
- The associated economic impact of fiber-induced failures.

The surveys indicated that life-critical services, such as hospitals, were already protected against contamination. Their air-conditioning systems also provided isolation from airborne carbon fibers. For utilities, airborne carbon fibers would be expected to cause some failures in older equipment. In commercial institutions, exposure to carbon fibers would cause failures in working equipment, but computers containing critical records were adequately protected. Critical systems in many of the 21 industrial installations visited were equipped with high-efficiency filters or coated circuit boards that would provide effective protection against airborne carbon fibers. Continuous-process operations and assembly lines, where equipment failures could halt operations, had similar features adequate to protect against airborne carbon fibers. Most industrial installations were able to shift operations or to work around electrical failures in equipment without major cost. Where equipment failures occur frequently, interchangeable spare parts were generally available. The results of these surveys were combined in the analysis models with census data to calculate the economic impact of carbon fiber accidents.

Risk Assessment

The primary objective of the risk analysis was to estimate the annual risk to the public resulting from the use of carbon composites in civil aircraft during 1993. A

secondary purpose was to provide a framework for making decisions on composite material usage, material modification, and protection schemes. Two contractors independently developed methods for quantifying the potential cost of electrical equipment failures caused by airborne carbon fibers released from aircraft accidents. The analysis used data gathered in the NASA test program and incorporated the fiber release, fiber transport, and equipment vulnerability considerations previously described. This analysis concluded that the mean annual loss resulting from commercial aircraft accidents would be expected to be less than $1000. In a worst-case scenario the loss was calculated to be approximately $150 000; the probability of this scenario occurring however would be once out of 2000 aircraft accidents.

An analysis of the general aviation fleet, including helicopters, showed that accidents with carbon fiber structural components will result in annual equipment damage of about $250 with only once chance in 10 000 of exceeding $110 000.

Along with the potential damage to equipment, the studies assessed the probability of power distribution outages. The analysis considered the effect of carbon fibers released from a worst-case aircraft accident scenario on outages experienced by individual electrical utility customers. One carbon-fiber-induced outage was expected to occur for every 200 000 to 1 000 000 outages currently caused by lightning, tree contact, vehicular damage, etc.; therefore, the risk of power outages is considered negligible.

Conclusions

- The electrical hazard from carbon fibers accidentally released in an aircraft crash fire posed no threat to human life.
- Overall costs associated with carbon fiber release are predicted to be extremely low.
- The risk of electrical or electronic failures due to carbon fibers is so minimal that future exploitation of carbon composites in aircraft should be continued.
- Additional protection of aircraft avionics to guard against carbon fibers is unnecessary.
- A program to develop alternate materials specifically to overcome the potential electrical hazard is not justified.

DEPARTMENT OF TRANSPORTATION (DOT)

In that virtually no data were available concerning the vulnerability of typical civilian surface transportation equipment, the Research and Special Programs Administration,

Transportation Programs Bureau, tasked the Transportation Systems Center to assess the effects of accidental releases of carbon graphite fiber composites on these systems.

The Department of Transportation has completed an assessment of the potential risks associated with the use of carbon fiber composites in the surface transportation system and has evaluated the vulnerability of the surface transportation system elements to airborne carbon fibers. In conducting the risk assessment, studies were performed to predict the potential usage rate of carbon fiber composites in surface transportation, the frequency and severity of vehicle fires, and the expected carbon fiber release from the composite in a fire.

The DOT final report also includes the quantity and applications of carbon fiber reinforced plastic (CRP) in surface transportation, the frequency of release incidents and the quantity of carbon fiber released from surface transportation, the risk to society associated with these incidents, and the vulnerability of surface transportation to carbon fibers.

The vulnerability of electrical components of surface transportation systems was assessed by comparison with vulnerability data developed by NASA and DOD for similar electrical components. The report is numbered DOT-TSC-RSPA-80-10 and may be obtained through the National Technical Information Service (NTIS).

Potential Use of Carbon Fiber Composites in Surface Transportation Vehicles

Glass reinforced composite materials are used extensively in recreational boat hulls and some body parts of automobiles. Recent applications are in truck fenders. In these applications, the fiberglass is used to take advantage of its low cost. Chopped fibers are frequently used to facilitate manufacturing complex shapes while providing adequate strength. Carbon fibers have not been used because their high strength-to-mass ratio could not be exploited to offset their higher cost.

There is, however, a significant incentive which may well alter the cost trade-offs between metals and composites. The major driving force for evolutionary design change in the automobile industry is the legislated goal of 27.5 miles per gallon fleet average required of each car manufacturer by 1985. While downsizing trends and improvements in drive-train and engine technologies are expected to continue, it appears that the near-term goal will largely be achieved through component redesign and direct substitution of plastics and aluminum for steel parts. The possibility of more stringent fuel economy standards proposed beyond 1985 may require vehicle manufacturers to incorporate significant quantities of advanced composite fiber materials (ACM) such as carbon, aramid, and glass for a variety of load bearing and nonstructural applications. DOT's report covers

an in-depth study that examines, in part, the potential use of ACM in automotive structures based upon a "weight reduction/cost incentive" concept.

The economic incentive for use of carbon fiber composites in truck and rail freight applications primarily involve potential increases in cargo capacity and payload. These direct advantages could be realized by selective use of ACM in body components to reduce primary and secondary weights of empty vehicles. Since carbon fibers possess superior fatigue-resistant and self-lubricating qualities, it is anticipated that vehicle repairs would be reduced and would therefore enhance full-time fleet operations.

In examining rail transit and bus vehicles, only slight improvements in fuel economy are expected from the selective use of carbon fiber composites and are not considered significant inducements by vehicle manufacturers at this time to advance high performance fiber composite technology for those applications.

In all cases, both economic and performance incentives are sensitive to manufacturers' raw material costs, retail price of vehicles, and life cycle ownership costs. These factors were all considered in projecting carbon fiber use beyond 1985.

Construction

Epoxy resins have been the predominant matrix material used to make advanced composites for aerospace applications. These resins have slow cure times and are relatively expensive. Accordingly, they do not lend themselves to high speed automotive processing techniques. Other resin systems are being evaluated as matrix materials to lower the costs of ACM. Thermosetting polyesters and vinyl esters are being extensively examined as candidate materials for high volume production applications. These resins are relatively inexpensive and formulations exist that cure rapidly, and, therefore, are amenable to high speed mass production fabrication methods. There is also interest in thermoplastics as matrix materials that exhibit reasonably high temperature resistance (such as nylon). These thermoplastic resins lend themselves to rapid processing and to post-forming which can result in significant cost reductions.

In general, the mechanical properties of fibrous composites depend on the type(s) of fiber incorporated in the matrix, its volumetric concentration, and fiber orientation.

High strength fiber materials currently under investigation for use in surface transportation vehicles are available in a variety of forms; the selection of which form to use is dependent upon the desired strength characteristics of the composite part.

Selective blending or hybridization of these fibers when combined in a polyester, vinyl ester, or other resin matrix, could result in high performance automotive composite materials that possess the desired mechanical, chemical, and thermal properties as well as long-term serviceability features.

Discussions with fiber manufacturers, fabricators, and end-users indicate that depending upon specific component design and structural requirements, advanced composite constructions for passenger car and truck applications could consist of 25 to 35 percent resin by weight with the remaining fraction containing 10 to 30 percent unidirectional or cross-ply carbon fiber by weight and 45 to 65 percent continuous or chopped glass fiber by weight.

The utilization of hybrids in the form of modified sheet molding compounds and sandwich construction is expected to dominate the "automotive grade" ACM market.

Ultimately, the end-use item and prevailing economic constraints will dictate type, form, orientation, geometry, and loading of carbon fiber within the composite structure.

Carbon Fiber Release

The primary release mechanism for carbon fiber from surface transportation vehicles is expected to be from severe thermal degradation of the carbon fiber composite such as could occur in in-service vehicle fires or during vehicle disposal. Since the major use of carbon fiber composites in surface transportation is expected to be in automobiles and trucks, estimates of the frequencies, locations, and severities of automobile and truck fires were developed. In addition, tests were performed to characterize the release of carbon fiber from burning automotive-grade carbon fiber composites.

The results of tests indicate that the release of significant quantities of single carbon fibers is unlikely. When the composites were burned without agitation, the mass of single fibers released was found to be less than 0.1 percent of the mass of carbon fibers in the original composite. The average length of the released fibers was about 1 mm. Agitation of the burned composite such as might occur in fire fighting or disposal operations appreciably increased the mass of carbon fibers released; however, a large portion of the additional release was multiple-fiber balls.

Detailed examination of historical data from multiple sources indicated that the annual incidence of vehicle fires which could be expected to release carbon fibers was one in 1000 for automobiles and light trucks and one in 2000 for heavy trucks.

The greatest potential source of carbon fiber release from surface transportation vehicles is in vehicle recycling and disposal. Approximately 65 percent of the vehicles produced annually eventually enter the recycling system. This represents about 50 times the number of vehicles involved in accidental release of carbon fibers in a year. It also implies that large quantities of carbon fibers could be released near disposal plants unless such plants are equipped to control effluents. The Environmental Protection Agency is including vehicle recycling and disposal in its program to control carbon fiber release.

Carbon fibers could also be released if a truck transporting them from the fiber manufacturer to the composite manufacturer were to burn.[1]

Vulnerability of Surface Transportation

The results of vulnerability tests performed by NASA and DOD on a variety of electrical and electronic equipment have provided the basis for determining the vulnerability of surface transportation to airborne carbon fibers. Surface transportation was found to be virtually invulnerable to carbon fibers, primarily because protective measures are employed to assure reliable operation in the normally harsh service environments. In addition, many systems operate at low voltage and high current levels sufficient to burn out carbon fibers which might cross exposed conductors. Gaps between exposed conductors are also large compared with the length of fibers.

Automobiles, trucks, and buses were found to be invulnerable except for radios and even these are almost invulnerable.

The power and propulsion subsystem of electric rail transit equipment employ redundant elements to minimize failures and are designed to be fail-safe. Thus, they are for all practical purposes invulnerable to carbon fibers. Diesel-powered locomotives were also found invulnerable to carbon fibers.

Signal and control systems for both electric and diesel rail systems are similar. The basic elements of the signal and control systems consist of sets of relays with associated power supplies. The construction of the relays and the double-break circuit design make these systems relatively invulnerable to carbon fibers.

Ships and barges for water transportation were found invulnerable. The enclosures and coatings used for protection of shipboard electrical equipment against high humidity

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[1]Although this problem was not investigated by DOT, NASA did conduct tests in which spools of raw fiber were exposed to propane flames for 20 minutes (NASA ref. 9). Very small quantities (less than 0.01 percent) of single fibers were released. This proportion is much less than that used in the NASA risk assessment for aircraft components destroyed in fire accidents. A fire accident of a truck cargo containing 10 000 kg of raw fiber exposes a quantity similar to the largest quantity assumed in the NASA risk analysis for aircraft fires. The amount of fuel available in the truck to produce the fire is much smaller than available in the aircraft. Therefore, the mean economic impact from fibers released in a truck fire would be much less than the $1200 mean cost that can be derived from the NASA risk assessment sensitivity analysis considering a 1 percent fiber release rate.

and corrosive environments provide excellent protection against carbon fibers. Further, ships are unlikely to be exposed to any but self-generated fiber releases because they operate remote from other sources.

The National Risk From Carbon Fiber in Surface Transportation

The risk arising from carbon fibers released from fires in surface transportation vehicles was calculated for the year 1993. This was expressed as a monetary cost of failures in public service, industrial, and household equipment. The method and cost data were the same as those used in the NASA study on aircraft accidents except that the automotive accidents were distributed among counties in proportion to the population in each country. Buses and water transportation vehicles were assumed not to contribute to the threat because no significant use of carbon fiber composites was expected.

The results of the risk analysis indicate that the potential risks of economic losses due to carbon fiber releases from accidental fires in motor vehicles are relatively small primarily because very small quantities of fiber are likely to be released in a given fire and electrical equipment is generally not sensitive to the levels of fibers expected. The expected national risk was estimated to be only about $5600 per year for 1993, with the average loss per incident being on the order of a few cents.

Furthermore, due to the high number of accidental fires per year, the national risk estimate is not subject to much variation. For example, the probability of exceeding $56 000 loss in one year was estimated to be about 1/100. Although the possible consequences of a single fire can vary greatly, depending upon whether equipment failures do occur, the likelihood of such a failure is only 5×10^{-4} per incident.

It should be noted, however, that the risk estimates are subject to uncertainty from a number of different sources. These uncertainties were incorporated into the analysis and are enumerated below. Even when sensitivity analyses were performed to test the effect of these uncertainties, the risks were found to be reasonably low in comparison to other types of risks. For example, the annual losses due to motor vehicle accidents are on the order of $20 billion, whereas the likelihood of exceeding $4 million due to carbon fiber releases in motor vehicle fires in any one year is only 10^{-4} even in the worst-case fiber release scenario.

The chief areas of uncertainty are the fraction of fibers released from the total mass and the vulnerability levels of electronic equipment potentially affected. However, even the most conservative scenarios in our sensitivity analyses indicate that the overall national risk is low. Other areas of uncertainty include:

1. Carbon fiber usage – Clearly one of the factors which could not at this time be predicted is the quantities of composites which may eventually be used in surface transportation vehicles.

2. Projected usage could conceivably vary by a factor of 2 or 3 in terms of carbon fiber weight per auto. Knowing this, however, such variations were taken into account in the sensitivity analysis by varying the fraction of carbon fiber released given an accidental fire.

3. Number of fibers by weight – We assumed 10^9 single fibers per kilogram of carbon fiber potentially available for release, based on previous NASA estimates. Although this number could be as much as five times greater (with smaller fiber lengths), the uncertainty was again accounted for by varying the fraction of carbon fiber released.

4. Fraction of carbon fiber released – Recent test results indicate that the 1-percent figure used in our base analysis is extremely conservative, and that it is possible that no more than 0.1 percent of single fibers by weight would be released. Hence, the worst-case scenario, in which fiber releases were increased by an order of magnitude to 10 percent, can be considered an extreme upper bound on the true risk.

5. Accident probability – The extrapolation of Michigan data could result in as much as a 50-percent error in estimating the national accidental rate of fire in motor vehicles. Also, the number of cars carrying carbon fiber was assumed to be 57 percent of the fleet. The net uncertainty due to these sources might increase the total number of fires per year involving carbon fiber by a factor of about 3. This effect is still very small compared to some of the other uncertainties in the analysis.

Conclusions

- Very few carbon fibers are likely to be released from a given fire in an automotive vehicle because only small quantities are likely to be used in a given vehicle in the foreseeable future. However, the number of accidents is large compared with the number of aircraft accidents.
- Much larger quantities of fibers will be released from obsolete or damaged vehicle disposal operations unless they are carefully managed.
- Buses and marine vehicles are not expected to employ carbon fibers in significant quantities. Thus, they do not contribute to the carbon fiber risk.
- Electric and electronic components of ground transportation vehicles are essentially invulnerable to damage by airborne carbon fibers.

- The national rail transit system is virtually invulnerable to damage by airborne carbon fibers.
- The overall costs associated with carbon fiber release from ground transportation accidents are predicted to be very low.

DEPARTMENT OF ENERGY (DOE)

The Department of Energy was tasked with the responsibility for evaluating the vulnerability of electrical power generating and transmission systems, and to recommend protection requirements should they be necessary. The evaluation was performed for carbon fiber exposure levels predicted in the NASA study for civil aircraft accidents. The final report of the DOE is contained in a Westinghouse Electric Corporation Advanced Systems Technology Report entitled, "Study of the Effects of Accidentally Released Carbon Graphite Fibers on Electric Power Equipment," DOE contractor report, DOE-RA-29193-1, 1981. The study was conducted under DOE Contract Number DE-AC01-78ET29193.

Vulnerability of Power Transmission and Generating Systems

As a result of a perceived threat to the reliability of the nation's electric power systems a program to study the effects of accidentally released carbon fibers on electrical power equipment was undertaken to determine the vulnerability of system outage rates to carbon fiber contamination, and tests were performed to quantitize the contamination required to cause flashover of external insulation.

In July of 1978, DOE awarded a contract to Westinghouse Corporation to perform a comprehensive investigation which included the determination of carbon graphite fiber effects on control and instrumentation, generation, and external electrical insulation facilities such as typically found in electric power systems. Once these effects were known quantitatively, the vulnerability of electric power systems to carbon graphite fiber releases could be determined in terms of an increase in component failure rates due to accidental releases.

The report assesses these vulnerabilities, describes the effects of carbon fibers on individual component failure rates, and discusses the effect the change in component failure rates has on the power system reliability.

Detailed testing was also performed to determine the vulnerability of external insulation to carbon fiber contamination. It consisted of airborne contamination tests on distribution insulators, limited tests on suspension insulators which are commonly used for

transmission class voltages, and various tests to quantify the influence of fiber length, voltage stress, etc., on flashover characteristics. The investigation has been completed.

The data obtained and analysis performed during this investigation show that the change in system reliability due to an accidental release from burned carbon fiber composite is negligible.

Program Description

At the outset of the program, the DOE suspected differences in the vulnerabilities and mechanisms of failure for power plant and substation control versus external insulation. The power plant and substation control equipment is typically low voltage (less than 150 volts) and mounted in enclosures; external insulation typically operates at higher voltages (greater than 600 volts) and is located in an outdoor environment such that it is directly exposed to any airborne fibers. For this reason the program was organized to perform two separate analyses, one for the evaluation of power plant and substation control vulnerability, and one for the evaluation of external insulation systems' vulnerability.

Other programs conducted under the same special President's Task Force as this investigation, and which were directed by the National Aeronautics and Space Administration (NASA), generated fiber exposure performance data for equipment which was similar to the equipment used in power plant and substation control systems. These data derived from other programs were used to determine control component failure rates for electric utility applications.

There were no substantial data available from any sources on the performance of external insulation under exposure to airborne carbon graphite fibers. Hence, DOE's contract with Westinghouse Electric Corp. included a test program to generate the required data for external insulation performance under fiber exposure.

The data obtained from this test program were used to determine probability distributions for the exposure levels necessary to cause the failure of various transmission, distribution, and substation insulators.

The electric power system vulnerability analysis was segregated into a power plant and substation control vulnerability analysis of external insulation. The results of these analyses are expressed as incremental component failure rates as compared to the failure rates typically experienced by electric utilities due to all other causes. Where possible, both component failure rates and customer outage rates were estimated since, due to the redundant designs of electric utility systems, a component failure does not necessarily imply a customer outage.

Vulnerability Evaluation

The power system evaluation assessed vulnerability of generation plants, substation controls, and external insulation to carbon fibers. Generating plant vulnerability was determined for the various types of power plants including: nuclear power plants, coal fired power plants, oil- and gas-fired power plants, hydroelectric power plants, and gas turbine generators.

Each type of power plant and substation was evaluated to determine fiber transfer functions, i.e., the ratio of the amount of fiber entering equipment enclosures to the amount of airborne fiber surrounding the plant for each area where critical equipment operates.

The vulnerability of electric utility control equipment to carbon/graphite fibers was estimated using NASA test results from the program which tested similar equipment. The results available from NASA provided the average amounts of fiber required to fail generic classes of equipment. These data were used directly to determine the performance of the control equipment used in the electric utility industry.

A conservative exponential probability distribution model was used to estimate the failure probability for each item of equipment exposed to the airborne carbon fiber that could enter a power plant following a nearby release. Fiber release characteristics were based on worst-case conditions and were determined through laboratory experimentation by various contractors funded by NASA.

Since in every plant some generic type of equipment, such as analog and digital electronic control systems was more vulnerable to carbon fiber than other plant equipment (an order of magnitude or more), the vulnerability analysis was based only on the most critical plant component. The resulting failure probabilities for this equipment were so small that further analysis was unnecessary.

Results indicated that the probability of inducing a power plant or substation outage due to control or equipment failure is on the order of 10^{-5} to 10^{-7} per plant exposure incident for the worst case and average release scenarios, respectively. If a power plant or substation were exposed once a year to a worst case release for every year of its estimated 30-year life, then only between 1×10^{-5} to 2.4×10^{-2} total failures can be expected over the entire 30 years. Considering the actual situation in which between 2.0 and 3.8 releases are expected nationwide every year from civil aircraft accidents the maximum expected number of plant outages is on the order of 2.8×10^{-5} to 1.2×10^{-7} per year. This pales to insignificance compared to the utilities' power plant and substation forced outage rates currently experienced due to nonfiber related causes. Power plants are typically out of service 15 percent of the time due to causes not related to carbon

fibers. The increase in power plant outages due to accidental releases of carbon fiber, therefore, is so small as to be nonexistent.

The vulnerability of external insulation was evaluated separately. External insulation being directly exposed to the outdoor environment can be expected to experience higher exposures to carbon fibers than the generating plant and substation control equipment discussed previously and the failure mechanisms are different. The vulnerability analysis for external insulation was performed similarly to the evaluation of power plant and substation control equipment vulnerability. Based on results from the testing program an exponential probability and distribution was used to determine insulator failure probability at the exposures postulated by NASA.

To determine the insulation system's vulnerability, the propagation of fiber and fiber densities proposed by NASA for an accidental release from civil aircraft accidents were used. The flashover probability for a single insulator at each fiber density level defined in the NASA release was applied to the estimated number of insulators exposed to each density level. The cumulative probability between the failure rates of the insulators exposed and the probability of exposure levels resulted in the probability of an insulator failure per accidental release of fibers. This combined probability of an insulator failure was then compared to typical insulator failure rates experienced from other causes.

The vulnerability analysis for external insulation was performed on transmission, distribution, and substation classes of insulation. These classes are differentiated by operation voltage, physical size, and the shapes of the insulator structures.

Based on an assumed 900 distribution-class insulators per kilometer and a 20-square kilometer area (a reasonable suburban distribution system model), the results of this analysis indicate that the failure rate for distribution class insulators due to a serious release each year is 8.6×10^{-2} insulator failures per year. In other terms, if a release occurred every year in the vicinity of a hypothetical suburb, once every 12 years an insulator would experience a flashover. This compares with 70 insulators per year which fail due to causes other than an accidental fiber release.

Similar analyses were performed on transmission-class insulation and on substation insulation systems. In the case of the transmission analysis a typical 50-km long transmission line was assumed. The transmission line was exposed to the fiber release along 3 km of its length based on NASA release data. The substation was assumed to be a three-bay substation with 90 insulators. In both of these analyses, the exposure levels used assumed an accident near the facility.

In order to place the vulnerability analysis results in perspective with failures and outages of facilities due to other causes, a summary table was prepared and is shown as table I. This table itemizes the anticipated component failure rates in a facility due to a

release which occurs near the facility (within 3 km) and which liberates an exposure of 1×10^3 fiber-sec/m^3. Both of these release characteristics are conservative and are expected to result in high rate of failure estimates. In the third column of the table typical facility outage rates currently experienced in the electric power industry for non-carbon fiber induced outages are presented. The fourth column presents the incremental percentage of facility outages which could be attributed to carbon fiber releases based on the above assumptions with an annual incident near the facility.

TABLE I.- SUMMARY OF CARBON/GRAPHITE FIBER-INDUCED POWER SYSTEM FAILURES

Type of facility	Probability of component failure per carbon fiber release (1)	Typical facility annual outages due to other causes	Increase in facility failure rate assuming one release per year near facility, percent (2)
Power plant and substation controls	1×10^{-7}/release	8/year	1×10^{-8}
Transmission line[3]	5.4×10^{-4}/release	1/year	5×10^{-4}
Distribution line[4]	8.6×10^{-2}/release	70/year	1×10^{-3}
Substation insulation	9.0×10^{-4}/release	0.6/year	2×10^{-3}

[1]Assumes release within 3 km of facility.

[2]Assumes component failure results in facility failures.

[3]Assumes 50-km line with 3 km exposed/release.

[4]Assumes 20-km^2 exposure area in distribution system.

The results presented in this table predict abnormally high incremental facility outage rates for the following reasons:

- The results are based on one release occurring near each facility (within 3 km) per year. Considering the numbers of each of these facilities in the United States and the 2.0 to 3.8 releases from civil aircraft accidents nationwide postulated by NASA, the resulting facility failure rates are considered extremely conservative.

- Each release is assumed to generate an exposure of 1×10^3 fiber-sec/m^3 which is considered by NASA to represent a maximum value, for the electric power system environment. The release distribution is skew and 95 percent of all accidental releases will be less severe than 10^3 fiber-sec/m^3.

• A single component failure is assumed to result in a facility outage, which is contrary to the electric power industry's design practice and equipment redundancy requirements.

Based on these assumptions, the actual increases in facility outage rates derived in table I are thought to be inconsequential when compared to existing facility outage rates in the electrical power industry.

Fiber Release Characteristics

In order to approximate and assess the vulnerability of electric power systems to accidental carbon/graphite fiber releases the characteristics of these releases had to be established. Discussions were held between NASA, who had funded release characteristics studies, DOE, and Westinghouse, our program contractor, to determine the release characteristics to be used.

As a result of the NASA-funded work performed up to this meeting, an exposure level of 1×10^3 fiber-sec/m^3 was determined to represent a maximum exposure which would be representative of at least 95 percent of the release incidents postulated. In other words, 95 percent of all incidents would liberate an exposure less than 1×10^3 fiber-sec/m^3 at points more than a few hundred meters from the center of the accident.

Since, at distances less than a few hundred meters from the accident center, the power system components would be in jeopardy from the aircrash itself, an exposure level of 1×10^3 fiber-sec/m^3 was selected for universal use in the overall evaluation of power system component probability of failure.

Based on later tests, the exposure levels required for a high probability of any electric power system component failure were found to be many orders of magnitude above this selected exposure level.

Testing Program

To obtain failure data for external insulation systems, a testing program was initiated by the Department of Energy with Westinghouse. During this testing program, probability of flashover was determined for various types of external insulation when exposed to varying degrees of airborne carbon fibers.

A test chamber was constructed to simulate accidental fiber release conditions. The chamber provided uniform dispersal of airborne carbon fibers and permitted continuous viewing of tests. The initial tests showed that insulators were relatively invulnerable to the carbon fiber release conditions postulated by NASA. To decrease test times, testing was performed with longer fibers and higher concentrations than originally predicted by NASA release scenarios. Trends were then established to extrapolate the data

to conditions more representative of an accidental release by performing a number of tests with the shorter fiber lengths.

Analysis of the test data determined that a representative probability distribution for failures caused by a fiber release on external insulation can be modeled by a Weibull Probability Distribution. However, an exponential probability distribution was used to estimate flashover probability in the vulnerability assessment because it predicts more conservative (higher) failure probabilities at the low exposure levels actually experienced from a release than would a Weibull Distribution.

External insulation is classified by the voltage level at which it is used. The test program included actual insulation samples typical of distribution-class insulation (under 35 000 volts), with the performance of transmission class insulations extrapolated based on the lower voltage tests. The procedure used in this extrapolation was to categorize the types of insulation used at transmission voltage levels and to determine the typical electric field stresses normally encountered. That the fiber deposit density on the insulation was a function of the electric stress had been established in the test program. Data were then accumulated and tabulated for insulations from distribution to transmission voltage levels; and it was demonstrated that the average voltage stress across the high voltage insulation is similar to that on low voltage insulation. Therefore, a reasonable assumption was formulated that transmission failure rates under carbon/graphite fiber exposure are similar to distribution-class insulation. Additional tests were carried out over a voltage range to verify that this was a reasonable assumption.

The results of these tests and analyses illustrated that insulator flashover is expected to occur at exposure levels 1×10^4 to 1×10^5 times the maximum exposure postulated by NASA scenarios. Therefore, the test program results established the basis for the conclusion that, under NASA-postulated release conditions, external insulation failures are expected to be highly unlikely.

Explanation of Statistics

An exponential probability distribution was used to model failures for both power plant controls as well as external high voltage insulation.

When a single fiber can cause the failure of a device, the exponential probability distribution provides an excellent failure model. Single fibers have been demonstrated to cause failures during the NASA tests of very low voltage equipment because they bridge the short contact-to-contact spacings present in these devices. These failure modes occurred along with multiple fiber failure modes in the same device. For the sake of conservatism NASA chose to use the exponential probability distribution for modeling all

low voltage equipment. That conservative practice has been continued in the DOE analysis of power plant and substation control equipment which utilized much of the NASA data.

Typical electrical power system high voltage insulation tested by DOE has large air clearances relative to the length of the fibers released. Therefore, several fibers must be present and bridge the clearance for a failure, which implies a higher minimum exposure to produce device flashover. This mode of failure is best described by a Weibull probability distribution. One of the Weibull distribution parameters is a variable which describes the estimated finite exposure below which failures would be extremely unlikely to occur. Accurate determination of this parameter by test is required. On the other hand, the exponential distribution assumes a more continuous probability at the low values of exposure.

Because of this conservatism, the exponential probability model was used in the data analysis of high voltage insulation. Because of the extremely low failure probability levels predicted by the more conservative exponential probability model, additional testing to determine Weibull parameters was considered to be unwarranted.

Conclusion

From the results of this DOE program it is concluded that the accidental release of carbon/graphite fibers, in the scenarios as postulated by NASA, does not constitute a significant hazard to electric power generating plant control systems, to substation control systems, or to outdoor high voltage insulation such as transmission lines, distribution lines, and substation insulation.

DEPARTMENT OF DEFENSE

A Joint Technical Coordinating Group (JTCG) on carbon/graphi . fiber studies was chartered to manage and coordinate tri-service activities. The group effort was broken into functional areas covering: Theories, Properties, and Effects; Vulnerability and Testing; Protection and Specifications; and Accidental Release.

The Theories, Properties, and Effects Subgroup was to review, apply, and extend applicable theories as well as identify empirically derived parameters to correlate the experimental results with the theories. A Basic Effects Handbook was published, and extensive data as well as predictive equations were supplied to the other subgroups. The phenomena are sufficiently understood so that single-fiber length susceptibility may be predicted for any system.

The Vulnerability and Testing Subgroup was to identify and rank subsystem/system targets, define vulnerability criteria, conduct tests, develop laboratory instrumentation,

and perform total system vulnerability assessments. They were also to determine the biomedical response. This group developed a vulnerability assessment methodology along with laboratory instrumentation which can be used to determine if a system is susceptible and its vulnerability at some threat level. Biomedically, the carbon fibers are an irritant, but no evidence was obtained that indicated a potential for inducing carcinomas. However, smaller fibers, such as can be released by burning composites, were not included in the biomedical research.

The Protection and Specifications Subgroup was to evaluate detectors, develop and evaluate filters, and evaluate decontamination and neutralization techniques. They were also to recommend interim design guidance, specifications, and standards for incorporation in the tri-service acquisition process. Portable survey meters for on-site counting of fibers have been developed as well as ball detectors for laboratory test purposes. Filters were found to be quite effective when installed and maintained properly and a non-bypass filter holder was designed. Polyacrylic acid (PAA) was found to be an effective hold-down fixant for use at aircraft crashes, and a military specification is being prepared. A specification tree was developed which indicates which specifications and standards could be affected by incorporating carbon-fiber protection requirements.

The Accidental Release Subgroup identified the fibers/composites being used in the military and determined their ignition temperatures, sustained burning temperatures, fiber release characteristics, residue forms, resistances, settling velocities, and distribution characteristics. Burn tests were performed with and without an attendant explosion, and the time dependence for release of fibers was determined. With this information, risk assessments were performed to bound the accidental release problem for the Army, Navy, and Air Force. The assessments were performed by the Army, for the Army, by TRW, Inc., and the MITRE Corporation, for the Air Force and by Arthur D. Little, Inc., for the Navy. DOD and NASA, who were invited to share DOD data, agreed for risk assessment purposes to use 1 percent of the initial composite mass as the quantity of fibers released for the burn only scenario and 3.5 percent of the initial composite mass for the burn/explode scenario.

The JTCG recommended, in part, that:

- Approved military hold-down/cleanup procedures should be used in the event of crashes of civil aircraft as joint-use airports known to have carbon fiber composites on-board.
- The services should monitor their development programs to determine if any future aircraft designs begin to use sufficient quantities of carbon fibers such that the Military Risk changes significantly.

- Disposal procedures should be coordinated with EPA through the Defense Logistics Agency.
- Fixant should be used on carbon-fiber aircraft crashes if necessary.
- The Navy and Air Force should continue to collect composite accident data and disseminate guidance on cleanup and disposal.

Transmittal of the Final Summary Report of the Joint Technical Coordinating Group to the Director, Office of Science and Technology Policy, concludes DOD responsibilities in the program as tasked in the Action Plan.

ENVIRONMENTAL PROTECTION AGENCY (EPA)

The Environmental Protection Agency (EPA) has principal responsibilities for (1) studying the potential impacts of carbon fiber disposal and (2) investigating and developing environmental and industrial monitoring equipment and safe techniques for disposal of both raw carbon fibers and the composite materials made with carbon fiber.

EPA's portion of the overall program is divided into two subprograms: Characterization and Measurement Technology, and Waste Management Technology Development.

Characterization and Measurement Technology

The research and development effort in Carbon Fiber Characterization and Measurement Technology is carried out at EPA's Environmental Sciences Research Laboratory in Research Triangle Park, North Carolina. The program consists of seven projects which are intended to develop capabilities for source and ambient air monitoring of carbon fibers released from manufacturing and waste disposal facilities. Each of these projects was initiated in 1979. The source monitoring projects will be completed by 1981, while the ambient-air monitoring ones will be completed by 1982. A brief summary of each follows.

Carbon Fiber Emissions Characterization

The objective of this 2-year study is to characterize the physical and chemical properties of carbon and graphitic fibers emitted during manufacturing, processing, accidents, and waste disposal activities.

Emission samples were taken at various stages of winding, weaving, pre-pregging, composite drilling and reaming, and sanding and routing. The samples were analyzed for fiber number and emission rates, and chemical and physical properties. Initial results indicate that weaving operations emit about 0.014 percent of the fiber material processed.

Early phases of this project show that during incineration of composite material, nearly all of the carbon fibers become available for release at temperatures above the combustion temperature of the binder. Only at much higher temperatures (above 800° C) are most of the fibers totally or partially destroyed by burning. At intermediate temperatures, the fibers are released with the combustion products.

Electrical properties of several types of carbon fibers have been examined in detail. Polyacrylonitrile (PAN-type) fibers are typical of those with diameters in the range from 6.5 to 8.0 μm. For this type of fiber, the electrical resistance of individual fibers is about 7.9×10^3 to 24.6×10^3 ohms per centimeter of fiber length.

Fibers from 0.15 to 1.25 cm long charge inductively in an applied electric field. In fields of relatively low strength, the fibers form chains that can bridge between electrodes when the gap is shorter than 3 fiber lengths, thus forming a short circuit. The frequency of chain formation increases with increasing fiber concentration. In circuits where sufficient voltage and power are available, the fibers will burn off when bridging occurs, but in many low-power circuits used in solid-state devices, component failures and circuit-malfunctions will occur when fibers form a fiber short circuit between components.[2]

This project is scheduled for completion in June 1981.

Sampling and Analysis Techniques Acceptable as a Reference Procedure

The objective of this study is to develop and validate methods for the identification and measurement of carbon fibers (number of fibers, size, range, and mass) emitted from manufacturing, processing, and incineration sources.

Experimental work based on laboratory-prepared mixtures of carbon fibers and other particulate matter in air revealed that light microscopy provides a definitive method for carbon fiber detection and measurement. Subsequent experimental work, performed on samples collected at various carbon fiber fabrication, processing, and manufacturing operations confirmed that the fibers are readily identified by the light microscope and can be easily distinguished from other particulate matter. A tentative measurement and analysis procedure was adopted. To test the procedure, field-site sampling was performed at six carbon fiber composite fabrication and processing facilities. The samples were then analyzed for fiber count, length, and diameter.

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[2]The effects of the described phenomena have been quantified in NASA, DOD, and DOE carbon fiber test chamber experiments used to obtain data for their risk analysis.

In other experiments carbon fiber composites were incinerated with municipal refuse. Fibers in the emission were collected in three cyclone catches, separating them from the bulk mass of other particle emissions collected. Electron microscope analysis showed the diameters of the carbon fibers to be considerably reduced compared to similar fibers before incineration.

The experimental work on this project should be completed by the end of this year.

Instrumentation for Continuous Monitoring of Carbon Fiber Emissions

This work is being conducted in two phases. The objective of the first phase is to evaluate currently available carbon fiber measuring techniques for application to continuous monitoring of carbon fiber emissions. The objective of the second phase is to develop and evaluate prototype monitoring instrumentation. The first phase is now nearing completion and the second phase is in progress.

The first phase included reviews of NASA risk studies, carbon fiber manufacturing operations, and laboratory studies of machining and incineration of carbon fiber materials. These studies indicated that the characteristics of emitted fibers can vary widely depending on the manufacturing or incineration processes used. Lengths of emitted fibers may range from 10 μm to 100 mm. These wide variations suggest that the monitoring systems may require two or more sensing techniques to cover the range of fiber sizes. Two types of monitoring systems may also be needed: one to provide the needed specificity when other particles, including noncarbon fibers, are major constituents of the emissions, and the other to be used where emissions contain carbon fibers almost exclusively. Interim reports on the first phase work are expected by the end of December 1980.

Under the second phase effort, a charged-grid technique for measuring carbon fiber concentration and deposition is currently being developed. The grid consists of a set of close-spaced and open-spaced parallel electrodes with high voltage applied between adjacent electrodes so that a carbon fiber shorting between the electrodes will initiate an arc. The current to the electrodes is monitored to count the number of arcs (fibers) over a given time interval. Various grid configurations have been constructed and used with good results. Although the demonstrated lower size limit of the technique has been 1 mm, the method seems promising and its use with shorter fiber lengths will be investigated.

Additional second-phase efforts are planned to complement the charged-grid technique studies. The objective is the development of a carbon fiber emissions monitoring system adequate for all anticipated needs. The work is scheduled for completion by July 1982.

Optical and Chemical Measurement of Carbon Fibers

The objectives of this project are to investigate the suitability of the existing sampling equipment and techniques such as the dichotomous sampler for collection of carbon fibers; to develop fiber measurement methods based on microscope and light-scattering techniques; and to develop a combustion technique for measuring carbon fiber concentration.

Samplers used to collect ordinary ambient aerosols are being investigated to evaluate their suitability for collecting carbon fibers. This evaluation includes experimental studies of transfer characteristics of sampler inlets. Several inlets now in use and designed specifically to reproduce size fractionation of ordinary aerosols were found to be unsuitable for carbon fibers, with the result that fiber size distributions are not strictly preserved in the process of size classification.

Many conventional aerosol samplers collect the particles on membrane filters. To exploit this means of collection, methods have been developed for counting and measuring carbon fibers with an optical microscope. This work is also scheduled for completion in December 1980.

In subsequent work under this project, the use of a carbon combustion analyzer will be investigated as a means of measuring the concentration of carbon fibers collected on a filter, and the use of light-scattering techniques will be investigated as a means of measuring concentration, and possibly length distribution of carbon fibers oriented on a collection substrate. The combustion analyzer work is scheduled for completion in September 1981, and the light-scattering work in September 1982.

Development of a Generator and Low-Cost Sampler

The purpose of this project is to develop and evaluate a prototype, inexpensive ambient sampler for carbon fibers. A generator for producing a high concentration of carbon fiber aerosol for testing the sampler will also be developed.

The low-cost sampler designed for the special purpose of carbon fiber collection is needed because existing aerosol samplers have limited application for carbon fiber collections. The design will incorporate two key elements. The inlet will be as well designed as possible for the aerodynamic size range of carbon fibers, and the collection substrate will be highly efficient for carbon fibers but relatively inefficient for other ambient aerosols.

Work is also proceeding on a generator for producing relatively high concentrations of polydisperse carbon fiber aerosols used in testing the sampler. The generator is

based on length reduction of carbon fiber filaments in a micro-mill, followed by aerosolization in a fluidized bed. The generator is scheduled for completion in December 1980.

The overall project is scheduled for completion in August 1982.

Development of Continuous or Semicontinuous Measurement Methods for Carbon Fibers

The objectives of this project are (1) to develop and test a prototype sampling and analysis system, based on induction charging, for the continuous or semicontinuous measurement of ambient carbon fiber aerosol, and (2) to develop a laser-based device for generating carbon fibers of uniform length to be used in calibrating the measurement system.

Work is proceeding on the design of an instrument for measuring the lengths of individual carbon fibers sampled from the ambient environment. The measurement principle is induction charging. To increase collection efficiency the instrument configuration is a repeating pattern of cylindrically symmetric "unit cells," each having a charged center wire surrounded by parallel uncharged wires.

The accurate calibration of such an instrument requires a generator that can produce known quantities of carbon fibers of uniform length. A semiautomatic device employing high-intensity laser cutting of single filaments to precise lengths has been fabricated and successfully tested. With this device it has been possible to generate fibers with uniform lengths from a few millimeters to less than 50 micrometers.

Development of the laser-based cutting device is nearly completed. Fabrication and evaluation of the "unit cell" monitor is scheduled for completion in March 1981. Development and testing of the prototype sampler-analyzer system is scheduled for completion in August 1982.

Generation and Characterization of Carbon Fiber Aerosols

The objectives of this project are to characterize carbon fibers released in breaking and grinding operations, to evaluate candidate methods for measuring carbon fibers, and to develop and test a prototype of a selected measurement method.

The aerodynamic diameters of particles produced by mechanical grinding of carbon fiber filaments have been measured. Mass median aerodynamic diameters are considerably smaller than the geometric diameter of the filaments (8 μm), indicating that grinding operations split the fibers as well as reduce their lengths.

A design is being formulated for a continuous carbon fiber monitor employing vertical elutriation and optical diffraction scattering.

The characterization of fibers was completed in July 1980. The evaluation of candidate measurement methods is scheduled to be completed by January 1981, the development of a breadboard of a selected measurement technique by September 1981, and development of evaluation of a prototype continuous monitor by November 1982.

Waste Management Technology Development

The Carbon Fiber Management Technology Program objectives include (1) assessing the likelihood of damaging releases of carbon fibers from conventional solid waste processing, resource recovery, and disposal technologies, and (2) determining how to modify these technologies or develop new technologies to safely dispose of carbon fiber-containing materials.

The program currently consists of five projects, four of which were initiated in 1979. One of these ongoing studies is investigating the economic implications of carbon fiber disposal in municipal wastes. Interim results show that on the average, carbon fiber in consumer goods will likely compose much less than 1 percent of the municipal waste being incinerated in 1990. The average economic impacts of carbon fiber release from municipal incinerators using conventional control equipment was found to be correspondingly small. These results indicate that the electrical and mechanical impacts of carbon fiber release from municipal incinerators are not likely to be significant. However, short-term high-percentage loading of carbon fiber material in municipal scrap could occur. There is presently no accurate data available on how much carbon fiber may exit a stack or how well air pollution control devices currently in use remove the carbon fiber from stack gases. For this reason a fifth project is being initiated to sample carbon fiber releases from a prototype incinerator and determine the collection efficiencies of four types of conventional emission control devices.

Status, Trends and Economic Implications of Carbon Fiber Material Use

This two phase project was initially intended to quantify the current and projected production and use of consumer products containing carbon fibers, and to evaluate the potential impacts of carbon fiber products. The first phase, which was completed in 1980, investigated impacts on the surrounding community from incineration of carbon fibers in municipal wastes. The impacts were quantified, where possible, in terms of their potential economic costs. Health effects, electrical failures, and mechanical impacts were investigated. It was found that potential health effects cannot be quantified

because sufficient data are unavailable. The annual economic cost of damage in the form of electrical failure and mechanical problems that would result from the incineration of consumer goods containing carbon fiber materials was found to be negligible. This is true even when it is assumed that all such consumer goods are disposed of in municipal incinerators (as opposed such options as landfilling).

In view of these first phase results, it was decided to redirect the project to study industrial disposal practices of carbon fiber material, instead of doing more detailed research into the economic impacts of disposal by municipal incineration. Little is known at present about the extent to which various disposal techniques are used in the industrial sector.

In both phases of this study work is being coordinated with the Department of Commerce so that existing data bases on carbon fiber usage can be utilized and augmented.

The final report of this project is expected to be completed early in 1981.

Data Base Review and Assessment of Carbon Fiber Release Into the Environment

The objective of the project is to determine the potential environmental impacts arising from the introduction of carbon fiber composite materials into American commerce. Each of seven task areas was developed in such a way as to focus on the effects arising from the disposal of carbon fiber materials, particularly those items which might enter municipal waste streams. Three of the tasks developed carbon fiber information bases for further efforts. One consisted of a literature search of recently published material in the following areas: release of airborne carbon fibers from incidents involving fires; current and developing applications of carbon fiber composites; research; properties of materials; and locations of manufacturers of carbon fiber or composites. Concurrently, two of the tasks reviewed both completed and on-going efforts by Federal Departments and Agencies.

Three other tasks were directly related to the problem of disposing of carbon fibers or composites. These drew upon the information developed in the first two tasks, data collected during on-site visits, surveys, and available expertise. Responses were developed in the following areas: characterization of typical life cycles for carbon fiber composites in various applications; analysis of disposal techniques and, in particular, of those techniques which may be used for incineration of municipal wastes; and estimation of the potential electrical and health effects which could result from the introduction of carbon fiber composites into municipal waste streams.

The seventh task was directed toward effective dissemination of information among the various Federal agencies and departments concerned with carbon fiber composites.

An inter-agency data exchange plan was developed, along with a Directory and Distribution List.

The final project report has been prepared and will be made available for public distribution through the National Technical Information Service.

Effect of Carbon Fiber Composite Material in Solid Waste Processing

Experimental work on the effects of carbon fiber composite materials in solid waste processing has been completed. The task involved the use of a pilot plant and associated equipment to investigate the effects of processing solid municipal waste containing projected typical amounts of carbon fiber wastes. The findings of these tests were based on the disposal of two different carbon fiber mixtures. The shredding of "pre-preg" carbon fiber material released substantial amounts of fibers from the grinding and processing operations. In the second series of runs "whole-piece" material was used. Data from these "whole-piece" runs are currently being analyzed, with preliminary results indicating that substantial carbon fiber releases may have occurred. Work on this project will be completed in 1981.

Program Coordination and Technical Assessments of the Carbon Fiber Waste Management Program

This project provides technical assistance and planning support to the Energy Pollution Control Divisions' (EPCD) carbon fiber research program. EPCD is directing the municipal waste carbon fiber studies in EPA's Industrial Environmental Research Laboratory. The project was initiated in October 1979 and will run through September 1982. On an annual basis, the project produces a review of all EPA carbon fiber research, including a status report for submission to OSTP. During FY-80 the project also undertook a review of the research needs for the evaluation of measures to mitigate the impact of carbon fiber on municipal solid waste technologies. In addition, the project team provided technical assistance for planning research on the measurement of carbon fiber emission control from municipal incinerators and evaluating alternative strategies for doing such control research.

Measurement of Carbon Fiber Emissions From Municipal Incinerators

The objective of this project is to see whether there will be significant emissions of carbon fiber from municipal waste incinerators if conventional air pollution control devices (APCD's) are utilized on incinerator exhaust streams. During FY-79 the emphasis of this planned project was shifted from sampling carbon fiber emissions from several different types of incinerators to testing the efficiency of carbon fiber control of four

different APCD's: a cyclone, a venturi scrubber, a baghouse, and an electrostatic precipitator. Shift in research emphasis was made based on the finding of other carbon fiber burn tests which indicated that there is a very high probability that carbon fiber emissions will occur from any type of incinerator and that, therefore, it is more important to study APCD performance in detail. The amounts and characteristics of carbon fiber residuals in other incinerator waste streams (e.g., ash) will also be determined and an analysis will be made of the resultant risk, if any, to the environment surrounding a typical municipal waste incineration facility that processes carbon fiber material. The contract for this project will be awarded in early 1981. The project will be completed in 1982.

Future Work

Future tasks which should be initiated by the EPA in FY-1982 or beyond involve:

- Evaluation of the legal, economic, environmental, social and political impacts of instituting necessary modifications to current and projected solid waste management systems. These impacts would be evaluated in light of the various risk assessments conducted previously by EPA and other agencies.
- Evaluation of carbon fiber disposal demonstration research in three areas: (1) full-scale incineration studies; (2) refuse derived fuel (RDF) and densified RDF combustion; and (3) evaluation of a small-particle collection device for controlling carbon fiber emissions.

A final decision on whether these research projects will be required will be discussed with the Director, Office of Science and Technology Policy, and based on the result of the five EPA-Cincinnati studies, particularly the one which will determine the carbon fiber removal efficiencies of conventional air pollution control devices.

DEPARTMENT OF COMMERCE

The Department was tasked, as part of the Carbon Graphite Composite Material Program, to establish a data base on the domestic production and use of carbon fiber with projections to 1985. Potential modification of trade classifications necessary to monitor imports and exports, and the assembly of existing data on foreign carbon fiber production and use were included in the tasking. Not knowing what the potential risk actually was, this information was felt to be necessary to scope the industry and provide a data file from which coherent Federal action could be based.

Commerce recognized the potential expectation of tailoring future efforts not only to fill committee needs but its own needs as the Federal agency responsible for this

relatively new commercial area. It was decided that Commerce should develop its own data base and analyses rather than simply relying on information available from the private sector. This was accomplished and fully documented in the Second Annual Report of 1979 (OSTP ref. 2). By the end of 1980 it was determined that committee requirements for such a data base were minimal and insofar as the committee was concerned this task could be concluded.

The National Bureau of Standards (NBS) was responsible for evaluating potential hazards of carbon fibers on computers, consumer goods, and other electronic devices and for developing remedial plans.

The NBS Institute for Computer Sciences and Technology (ICST) conducted a study of possible effects of carbon/graphite fibers on computers and associated equipment. The NBS Center for Consumer Product Technology (CCPT), under the sponsorship of the Langley Research Center (NASA), has completed their study on the effects of carbon fibers on various household appliances. Their findings are contained in NBSIR 79-1952, entitled "Study of the Effects of Carbon Fibers on Home Appliances," February 1980.

During 1980, NBS continued its assistance to NASA in the development of test methods for appliances requiring chamber testing and provided consultation concerning the performance of these tests. NBS also analyzed other potentially vulnerable electrical appliances and household equipment using electrical or electronic controls. Typical examples of types of equipment evaluated were: (1) equipment containing electronic ignitors and electronic flame sensors for gas and oil, and (2) electrical devices with air flow. No additional work relating to the evaluation of the adverse effects of carbon fibers by NBS was to be undertaken unless specifically requested by NASA or the Chairman of the Interagency Committee.

DEPARTMENT OF HEALTH AND HUMAN SERVICES

The Department of Health and Human Services/National Institute for Occupational Safety and Health (HHS/NIOSH) was given the responsibility to assess the carbon/graphite fiber exposure data, evaluate the health implications, and determine the need for further research. Continuing activities concerning carbon/graphite fibers are being conducted to characterize the fibers released from burning composite materials, and to assess toxicological and epidemiological data as related to fiber exposures.

Carbon/Graphite Release Studies

A primary concern was to quantify the risks to the public resulting from the use of carbon/graphite composites. Of the studies conducted by the respective governmental agencies on the OSTP committee and their contractor organizations, those performed by

the National Aeronautics and Space Administration (NASA) provided most of the documentation on potential airborne exposures to carbon/graphite fibers. These exposure data were accumulated as a result of studies designed to quantify the risks associated with the accidental release of carbon fibers resulting from an aircraft crash.

The tests conducted by NASA involved the burning of carbon/graphite composites to determine the number and sizes of released carbon fibers. (See appendix B.) These tests included small-scale laboratory research along with outdoor simulated aircraft burns. The studies were designed to characterize fiber sizes (>1 mm length) thought to be responsible for electrical interference of power supplies. Observations from the laboratory tests, in which composites were burned and subjected to mechanical agitation, airstreams, and explosives, indicated the release of single fibers up to 3.5 percent of the original fiber mass. Typical results from the outdoor fire tests indicated that between 15 percent and 60 percent of the original composite mass remained in place after the fire with single fibers accounting for only 0.2 percent to 0.6 percent of the mass. Likewise, in a shock tube test, in which various types of electrical and electronic equipment were exposed to burning composite material, single fibers accounted for 0.75 percent of the fiber originally available. Both the outdoor and shock tube tests indicated a small release of single fibers, with as much as 50 percent of the original composite mass consumed by oxidation in the fire. These outdoor tests confirmed the laboratory observations of the release of fibers under various test conditions.

Fiber lengths measured in these studies averaged between 2 and 3 mm, with few fibers longer than 4 mm. An investigation of fibers smaller than 1 mm in length indicated that these fibers constituted 67 to 74 mass percent of the total fibers released in undisturbed fires, and as high as 98 mass percent for those fibers released in fires accompanied by explosions. When fiber diameters were evaluated for fibers longer than 1 mm there was an observed reduction in size from the typical 7 to 8 micrometer (μm) diameter of the product material to an average of between 4.0 to 4.7 μm at a lower detection limit of 1.0 μm.

A more extensive study was then conducted by NASA to characterize those fibers thought to be potentially respirable (lengths <80 μm and diameters <3 μm) which were being released during the burning of composite materials. (See NASA ref. 32.) It was estimated that fewer than 24 percent of the fibers released during the composite burn tests fell into this size range. Likewise, a fiber size distribution performed by optical microscopy indicated an average fiber diameter of 1.5 μm and an average length of 30 μm. These dimensions were based on lower detection limits of 0.4 μm for diameters and 2.0 μm for lengths, and a length-to-width aspect ratio of ≥3:1.

Approximately 50 percent of these fibers had aspect ratios <20:1, with 85 percent <40:1. It was evident from the microscopy analysis that some of the carbon/graphite

fibers being released from the burning composite material were of a smaller diameter than that of the product material (normally 7 to 8 μm); this phenomenon was attributed to a fiber oxidation and fibrillation effect.

Based on the fiber size data collected during the outdoor burn tests, a laboratory controlled-burn experiment was conducted to investigate the mechanisms of fiber release and oxidation, and to find a means to collect and characterize released fibers (ref. 1). The results of the experiment indicated that, depending upon the fire condition, a certain percentage of the fibers will partially oxidize and fracture into small diameter (needle-like) fibers. Many of these released fibers, although not quantified in the study, appeared to have diameters <3.0 μm.

As a result of the fiber characterization studies, two studies were initiated in an attempt to quantify airborne fiber concentrations during the burning of carbon/graphite composites. One study used a theoretical approach based on fiber release data obtained in previous laboratory and outdoor burn tests. (See NASA ref. 32.) Only those fibers considered to be potentially respirable (<3.0 μm in diameter and >8 μm in length) were utilized in predicting fiber exposures. The number of respirable-size fibers generated per kilogram of carbon fiber released during an aircraft accident and burn was estimated to be 5×10^{11}, with a mass fraction of 5 percent of the total fiber released. Based on these criteria, an estimated peak exposure of 5×10^{6} fibers/m^3 was determined with an upper limit exposure estimated at about 3.2×10^{8} fibers-sec/m^3 for fibers within the smoke plume.

The other NASA study attempted to quantify and characterize fiber exposures during the burning of carbon/graphite composite materials by collecting air samples on a "Jacob's Ladder" suspended in the smoke plume (ref. 2). Sampling was performed using battery-operated sampling pumps which drew air (2.0 liters per minute) through a cellulose membrane filter. Filters were analyzed utilizing phase contrast optical microscopy at ×400 magnification with all fibers (≥3:1) counted (ref. 3). Based on a 20-minute burn time, concentrations were determined and these indicated a range from none detected to 0.14 fiber per cubic centimeter of air (fiber/cm^3). All fibers observed were ≥5 μm in length and <3.5 μm in diameter, with 77 percent of the fibers ≤1.7 μm in diameter.

Related Epidemiologic and Animal Toxicologic Studies

Ever since the first reported death due to pulmonary fibrosis resulting from asbestos exposure in 1900, and subsequent comprehensive studies indicating an association between asbestos and respiratory diseases, the cause and effect relationships have been intensely investigated (refs. 4 and 5). In one animal study using chrysotile asbestos, it was concluded that the fiber shape and size were more important factors in carcinogenesis than chemical composition (ref. 6). This theory was substantiated in another

animal study in which a series of different mineral dusts were injected into the pleural cavities of mice to test their relative fibrogencity (ref. 7). The degree of cellular granulomatous adhesions which were found between the lungs, diaphragm, and chest wall was dependent upon particle size and morphology. The highest degree of fibrosis within the granulomata was demonstrated using long fibrous minerals. The amount of fibrosis decreased with shorter fibers and particles.

The precise fiber dimensions required to observe pathologic responses have been impossible to determine experimentally because of the difficulties encountered in producing fibers of specific size (ref. 8). However, the results from some of the more recent studies suggest that long, thin fibers play an important role in eliciting a biological response. In a National Cancer Institute fiber implantation study, it was concluded that fibers <1.5 μm in diameter and longer than 8.0 μm in length may be the most important for production of pleural sarcomas (ref. 9).

Epidemiologic Studies

To date, no epidemiologic studies have been conducted on persons exposed to carbon/graphite fibers. Likewise, few epidemiologic studies have been able to differentiate the pathologic responses (e.g., pulmonary fibrosis, lung neoplasms) in man with regard to fiber types and dimensions. The following is a cursory review of those occupational studies conducted by HHS/NIOSH to determine health implications from exposures to various fibrous materials. Similar research studies have been conducted by other groups but are not included in this review.

<u>Fibrous glass (large diameter) (ref. 10)</u>.- Fibrous glass studies which have been conducted among workers producing fibrous glass of relatively large fiber diameter (>3.5 μm) have not shown an excess cancer risk. However, a slight excess mortality risk for nonmalignant respiratory disease, excluding influenza, has been observed.

<u>Fibrous glass (small diameter) (ref. 11)</u>.- A study of workers exposed to small diameter (<1.5 μm) fibrous glass is continuing for observation of any excess mortality. Latency from onset of exposure has been approximately 25 years, which is considered to be the minimum time period necessary for the initiation of both nonmalignant and malignant respiratory disease.

<u>Rock wool (ref. 12)</u>.- Results of an epidemilogic study of workers producing rock wool and slag wool suggest a possible increased risk of respiratory and gastrointestinal cancer with long latency periods (>30 yr). Observed fiber diameters indicated a median of 2.2 μm, with 75 percent of all fibers being <3.5 μm in diameter. Airborne fiber concentrations ranged from 0.10 to 1.95 fibers/cm^3.

<u>Wollastonite (refs. 13 and 14)</u>.- In a morbidity study conducted on miners and millers exposed to wollastonite (a fibrous monocalcium silicate mineral), several abnormal medical findings were discovered, but no definite association of wollastonite exposure and excess morbidity could be demonstrated. However, because of the small number of subjects ($N = 92$) studied and the short latency period (average 11.2 yr) from onset of exposure, the sensitivity of the study was low. Typical airborne exposures indicated a median fiber diameter of 0.22 μm with varying fiber lengths (0.3 to 41.0 μm).

<u>Fibrous clay (ref. 15)</u>.- The preliminary mortality study results of workers exposed to a fibrous clay (attapulgite) indicate no statistical excess mortality. Workers are currently being categorized by exposure concentration and latency to determine if a dose-response relationship exists. The median fiber sizes observed in airborne exposures were 0.07 μm diameter and 0.40 μm length with no fibers observed longer than 2.50 μm.

<u>Asbestos (ref. 16)</u>.- A morbidity study was initiated to study the health risks of workers associated with low level exposures to asbestos fibers during automotive brake servicing. The results of the study suggest no increase in respiratory diseases. A mortality study is being contemplated to determine if an excess mortality exists for this population. Exposures to asbestos for workers employed in this type of work indicate time-weighted average (TWA) exposures below the NIOSH recommended standard (of 0.1 fiber/cm^3). Most of the airborne fibers observed (>80 percent) were shorter than 5.0 μm in length with diameters 1.0 μm.

Toxicologic Studies

<u>Carbon fibers (refs. 17 and 18)</u>.- To date, two independent toxicologic studies have been conducted using carbon fibers. One study reported on the long-term toxicity of carbon fiber implants in rats and mice. Termination for those animals which survived was at 18 months for mice and 24 months for rats. Histological examination was carried out on all tissue sections from the implant areas and for specific organs removed at post-mortem examination. Only one malignant tumor (fibo-sarcoma) was found in relation to an implant. Fiber size data were not reported; however, it was assumed that the fibers used were of a commercially produced size (6 to 8 μm in diameter).

In the other study, guinea pigs were exposed to airborne chopped carbon fibers for time periods up to a maximum of 104 hours. About 99 percent of the airborne particles generated were nonfibrous and about 1.0 μm in diameter. Few of the airborne fibers observed were of a respirable size (reported as 1.0 to 2.5 μm diameter and <10 μm length) with most fibers $\geqq 10$ μm in diameter and >100 μm in length. Animals were sacrificed at intervals ranging from 1 to 144 days after exposure. Microscopic examination of lung tissue indicated the presence of four particulate types:

(1) Carbon fibers approximately 10 μm in diameter and >100 μm in length;

(2) Nonfibrous carbon particles with diameters ranging from submicron to several microns;

(3) Carbon fibers ranging in diameter from 1.0 to 2.5 μm and ≤ 15 μm in length; and

(4) Transparent fibers (unknown composition) typically 1.5 μm in diameter and up to 30 μm in length.

Most of the nonfibrous carbon particles observed in the lung tissues were in macrophages with most fibers found extracellular. No tumors were observed.

Fibrous glass (ref. 19).- NIOSH has initiated a chronic inhalation study of fibrous glass. Both rats and monkeys are being exposed using four different exposure parameters.

(1) Concentration 15 mg/m^3 – fibers 4 to 6 μm diameter/40 to 50 μm length

(2) Concentration 15 mg/m^3 – fibers 1 μm diameter/>10 μm length

(3) Concentration 5 mg/m^3 – fibers 1 μm diameter/>10 μm length

(4) Concentration 5 mg/m^3 – fibers 1 μm diameter/<10 μm length

This is an 18-month study in which pulmonary function tests will be given at periodic time intervals and with all animal sacrificed at the completion of the study for tumorigenic observation. After 15 months of the study, no significant decrease in pulmonary function has been observed.

Asbestos (ref. 20).- A chronic inhalation study with chrysotile asbestos shorter than 5 μm in length is currently under way at NIOSH. Both rats and monkeys are being exposed over an 18-month period to an asbestos concentration of 1.0 mg/m^3, 7 hours/day, and 5 days/week. After 15 months of the study, animal sacrifices have indicated asbestos fibers in the tissues, but no indication of fibrosis.

Discussion

Although the respirability of airborne fibers is not clearly understood, it is thought to be mainly dependent on the fiber diameter. Studies have suggested that the two major mechanisms of fiber deposition in the upper airways (gravitational settling and inertial deposition) are chiefly dependent upon particle aerodynamic diameter (ref. 21). Fibers with densities <3.5 g/cm^3 and diameters <3.5 μm may escape deposition by these two mechanisms and penetrate deeply into the lungs of humans.[3]

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[3]Carbon/graphite fibers have densities ranging from 1.7 to 2.0 g/cm^3.

Based on the current epidemiologic and toxicologic research with fibrous materials, it appears that fibers with diameters >3.5 μm have little effect in producing malignant diseases, and only a slight effect in inducing nonmalignant health risks in humans. Studies to date on carbon/graphite composite materials suggest that fibers released during the use of these materials are mostly >3.5 μm in diameter, except when exposed to high temperatures (900°C to 1100°C). As demonstrated during the burn tests of composite materials, a small percentage of carbon/graphite fibers are released with diameters <3.5 μm and lengths >10 μm. When exposures from outdoor burn tests (~20 minute duration) were quantitated for these small diameter fibers, concentrations appeared to be <0.1 fiber/cm^3. Based on a theoretical model, the carbon/graphite exposures when extrapolated for a potential aircraft burn,[4] indicated a release of small diameter fibers of 3.2×10^8 fibers-sec/m^3; and, if accompanied with an explosion, fiber release was estimated to increase by a factor of 3.5.

If we evaluate these exposures in the most restrictive manner, that is, comparing carbon/graphite fiber exposure data with the NIOSH-recommended occupational standard for asbestos, or, in a less restrictive manner, using the NIOSH-recommended standard for fibrous glass and other man-made fibers,[5] then the observed exposures to carbon/graphite fibers, to date, have always been some magnitude less than either of the NIOSH-recommended fiber standards.

The toxicologic mechanisms for the production of pulmonary fibrosis and respiratory cancer from exposure to certain fibers (e.g., asbestos, fibrous glass) are not well understood; however, a growing body of animal data suggests that these effects may be due to the fibers' dimensional morphology rather than physico-chemical properties. Numerous animal studies have shown that many types of fibrous materials produce fibrosis and tumors upon injection or implantation; yet, the exact delineation of fiber size characteristics necessary for animal tissue damage and tumor production is unknown. The ability of fibers with appropriate dimensional characteristics (diameter and length)

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[4]In the smoke plume, at a point close to the fire.

[5]The asbestos standard recommended by NIOSH is for a maximum occupational exposure concentration of 0.1 fiber/cm^3 (>5 μm length) for up to an 8-hour workshift with peak concentrations not exceeding 0.5 fiber/cm^3 based on a 15-minute sample period. The recommended standard for fibrous glass is for a maximum occupational exposure concentration of 3.0 fibers/cm^3 for up to a 10-hour workshift in a 40-hour workweek for fibers ≤3.5 μm in diameter and length ≥10 μm and for fibers >3.5 μm in diameter, airborne exposure concentrations should be limited to a time-weighted concentration of 5 mg/m^3.

to reach critical sites such as the pulmonary spaces or the gastrointestinal tract must be considered. In addition, respiratory clearance for different fiber types may be very important; differences in fiber clearance may be related to reactions with lung macrophages and to cytotoxicity of the material in question.

Recommendations

Based on the current exposure data for carbon/graphite fibers, and in view of the paucity of toxicity studies, it appears prudent that well-designed animal toxicity studies be performed with carbon/graphite composite materials which reflect the fiber characteristics observed in field and laboratory tests to date. Since the latency period from the onset of the first potential carbon/graphite fiber exposure to present, for either the general population or occupationally exposed persons, has probably been short (<20 years), and, because fiber exposures documented to date appear minimal, it does not seem appropriate at this time to conduct either a mortality or mobidity study of persons who were potentially exposed. Likewise, an appropriate population for study would be extremely difficult to assemble and characterize.

It is suggested that the best means for evaluating the potential health effects of carbon/graphite fiber exposures would be through animal inhalation toxicity studies in which at least two species are used to determine deposition, retention, and cause of death. Typical carbon/graphite fiber exposures (e.g., as a result of burning, cutting, grinding, etc.) and fiber characteristics (e.g., certain size parameters for diameters and lengths) should be utilized under animal lifetime conditions, with care given to determining the actual deposition and retention in tissues and the appropriate health-effect end points. Since a synergistic association is known to exist between asbestos fibers and cigarette smoking, it may be appropriate to conduct at least one study that combines exposure to carbon/graphite fibers and cigarette smoke (ref. 22).

In view of the environmental and health data, compiled to date it would be advisable to handle carbon/graphite composite materials and treat airborne fiber exposures in the same manner recommended by NIOSH for fibrous glass. Appropriate measures should be taken when working with carbon/graphite composite materials to minimize the potential for generating small diameter fibers and to control airborne exposures to the lowest feasible level.

THE OCCUPATIONAL SAFETY AND HEALTH ADMINISTRATION

OSHA has cooperated in a preliminary review of the production and occurrent of carbon fibers and attendant potential hazards. No regulatory action on this issue has been taken by the Assistant Secretary of Labor for Occupational Safety and Health and

none will occur unless future findings result in the identification of safety or health hazards as associated with the workers. Any contemplated regulatory action will be brought to the attention of the Director, Office of Science and Technology Policy. In this event, the Technical Support and Standards Development Directorates of OSHA will alter their standards setting priorities to accomplish any necessary regulatory action.

The control options for the Agency were outlined in the 1979 Annual Report (OSTP ref. 2). A discussion on hazard alerts, emergency temporary standards, and permanent standards was included. These options remain the same in 1980.

FEDERAL EMERGENCY MANAGEMENT AGENCY (FEMA)

The Federal Emergency Management Agency, insofar as its relationship with State and local officials is concerned, has informed and advised those officials of the potential problems inherent with carbon fiber composites. State and local agencies have also been requested to keep FEMA informed of incidents in their respective areas involving carbon fiber composite materials.

IV. FINDINGS

The Federal Government action plans for dealing with potential problems arising from the use of carbon composite materials emphasized three major objectives: (1) to understand the details of damage mechanisms to equipment and personnel, (2) to prevent the introduction of fibers in damaging quantities into the atmosphere, and (3) to modify materials to avoid damaging effects.

As the study progressed, the understanding of the electrical damage mechanisms improved rapidly. This understanding led to a logical underlying rationale that places the national risk into perspective. Key elements in this rationale are:

1. A representative accidental fire releases far smaller quantities of fiber than was originally thought, with a majority of the fiber being completely consumed by the fire.

2. The released fibers are typically quite short.

3. The fibers are dispersed over very large areas. Thus, the concentration of fibers is low except in the immediate vicinity of the fire.

4. Buildings, filters in air-conditioning systems, enclosures for sensitive electrical systems, and effective coatings inhibit the intrusion of fibers into otherwise vulnerable circuits.

5. Gaps between conductor pairs are generally proportioned to the voltage across them, and usually are several times the length of the fibers that gain entry. The exceptions are in low-voltage printed circuits, where in this case conformal coatings usually protect the circuitry.

6. The higher the voltage the more likely a fiber will burn out with little or no equipment damage.

7. Inherent or built-in redundancies in many electrical and electronic systems preclude breakdowns, even if one portion of a circuit is damaged or fails.

Many facets of the study were devoted to quantifying the qualitative comments in the foregoing. This led to the following specific conclusions for major sections of the American economy:

- Accidents of civil transport and general aviation aircraft are unlikely to release large enough quantities of single fibers to cause significant economic impact. Aircraft internal electric and electronic systems are essentially immune to failures from fibers attributed to this source.

- Individual fires of automobiles and trucks will release even smaller quantities of single fibers, even though many more vehicles and accidents may be involved. Automotive systems are immune to damage. Bus, rail, and marine vehicles are not expected to utilize enough carbon composites to present a problem and their systems are very well protected for other reasons.
- Power generation and distribution systems are not expected to use fibers. Internal controls and external insulators are such that the numbers of potential failures are several orders of magnitude smaller than those for other causes.
- Practically all household and industrial equipment was found to be invulnerable to single fibers of the sizes and exposure levels anticipated.
- No significant safety hazards were identified.
- The economic loss risk from the accidental release of carbon fibers is so low as to be clearly acceptable on a national basis and does not justify follow-on work to develop alternate materials.

One aspect of the overall problem that has not yet been quantified is the hazard created by disposal of vehicles and other products containing carbon fibers in municipal disposal systems. If disposal is by incineration, the process has the objective of reducing all combustible matter to its smallest volume. Conceivably, significant quantities of carbon fibers could be liberated, particularly when large volumes of automobiles containing tens of pounds of composites will be removed from the transportation system and annually disposed of. EPA is continuing its studies to quantify this situation, to monitor the atmosphere, to assess the efficiency of capturing fibers by present systems and, if necessary, to develop better controls or techniques.

Although no evidence has been found that airborne carbon fibers cause any physiological harm to humans or animals, efforts will continue by DHHS toward assessing this aspect.

V. STATUS OF AGENCY RESPONSIBILITIES

The National Aeronautics and Space Administration responsibilities concerning risk assessment for civil aircraft accidents, protection measures for commercial aircraft, and alternate and modified materials are concluded. Management support to the Director, Office of Science and Technology Policy, shall continue on an, as required, basis until terminated by mutual consent of the Director and the Administrator.

The Department of Transportation's responsibilities concerning risk assessment for surface transportation accidents and protection measures for surface transportation equipment are concluded. Responsibilities for aircraft accident reporting as previously established will continue.

The Department of Energy's responsibilities concerning power generation vulnerability and protection and power transmission vulnerability and protection are concluded.

The Department of Commerce's responsibilities concerning communication and computer vulnerability and protection, household equipment vulnerability and protection, and carbon fiber market, production, and analysis are concluded.

The Department of Defense's support responsibilities with relationship to the Director, Office of Science and Technology Policy, and the interagency committee are concluded.

The Department of State's responsibilities concerning the international aspects of monitoring foreign production of carbon fibers, U.S. import considerations, the issuance of suitable advisories to governments of countries producing or using carbon fibers are concluded.

The Environmental Protection Agency shall continue with its responsibilities concerning environmental and industrial monitoring for carbon fiber and carbon fiber disposal methods. Annual reporting requirements from the Agency to the Director, Office of Science and Technology Policy, shall continue as originally tasked.

The Department of Health and Human Services shall continue with its responsibilities concerning environmental health analysis. Annual reporting requirements to the Director, Office of Science and Technology Policy, shall continue as originally tasked.

The Department of Labor's Occupational Safety and Health Administration shall continue its responsibilities concerning industrial worker safety standards. Annual reporting requirements to the Director, Office of Science and Technology Policy, shall continue as originally tasked.

The Federal Emergency Management Agency shall continue its responsibilities for emergency procedures and carbon fiber incident analysis. Annual reporting requirements to the Director, Office of Science and Technology Policy, shall continue as previously directed.

The Office of Management and Budget shall continue its responsibilities for assisting participating agencies with necessary budget requirements and for assisting the Director, Office of Science and Technology Policy, in fulfilling the remaining program requirements.

The Director, Office of Science and Technology Policy, shall continue to be responsible for program direction and for central coordination, monitoring, and oversight.

The interagency committee for 1981 and 1982 shall be comprised of the OSTP, NASA, EPA, DHHS, DOL (OSHA), FEMA, and OMB. The Director, OSTP, shall continue as Chairman.

VI. APPENDICES

APPENDIX A – CARBON FIBER INTERAGENCY COMMITTEE

List of Representatives

OSTP

Ben Huberman
Wayne Kay

NASA

Leonard Harris
Henry Hertzfeld

DOL

Hays Bell

OMB

Kshitij Mohan

DHHS (NIOSH)

Lowell Harmison
Ralph Zumwalde

EPA

Benjamin Blaney
Kenneth Knapp

FEMA

Sue Perez

APPENDIX B – NASA RISK ASSESSMENT

The following section is excerpted from the NASA Special Publication, SP-448, Risk to the Public From Carbon Fibers Released in Civil Aircraft Accidents, 1980. Figures, tables, and reference numbers have not been renumbered from the original. All references cited in NASA SP-448 are listed in section VII of this report, along with reports from the NASA alternate materials studies.

NASA SP-448 EXCERPT

The NASA Langley Research Center (LaRC) was responsible for quantifying the public risk associated with the accidental release of carbon fibers from civil aircraft and for assessing the need for protection of civil aircraft systems from such fibers. Responsibility for the direction of the NASA LaRC study was assigned to the Graphite Fibers Risk Analysis Program Office. The Program Office sponsored and coordinated 19 studies conducted by NASA centers, private contractors, and other government

agencies listed in table II. The results of these studies are reported in over 50 NASA Technical Memorandums, NASA Contractor Reports, and reports by other agencies. This report summarizes these results and cites the supporting documents.

TABLE II.- PARTICIPANTS IN NASA LaRC PROGRAM

Participant	Area
Air Force Geophysics Laboratory	Fiber source test operations
AVCO Corporation	Fiber source
Bionetics Corporation	Fiber source Fiber transfer Equipment vulnerability
Boeing Commercial Airplane Company	Fiber source Aircraft vulnerability
Douglas Aircraft Company	Fiber source Aircraft vulnerability
The George Washington University	Statistical analysis
Jet Propulsion Laboratory	Instrumentation
Arthur D. Little, Inc.	Risk analysis
Lockheed California Company	Fiber source Aircraft vulnerability
NASA Ames Research Center	Fiber source Fiber dissemination
NASA White Sands Test Facility	Fiber source
National Bureau of Standards	Equipment vulnerability
ORI, Inc.	Risk analysis
Science Applications, Inc.	Fiber dissemination
TRW, Inc.	Fiber source
U.S. Army Ballistics Research Laboratory, Aberdeen, MD	Equipment vulnerability Fiber transfer
U.S. Army Dugway Proving Ground	Fiber source Fiber dissemination
U.S. Naval Surface Weapons Center Dahlgren, VA	Fiber source

These NASA studies were focused in the following areas, each of which is covered in a separate section of this report:

- Fiber Source
- Fiber Transport
- Vulnerability of Equipment and Shock Hazard
- Facility Surveys
- Risk Assessment

Included within "Fiber Source" are the necessary projections of future use of carbon fiber in aircraft and the character and amount of fiber released in the burning of carbon composites. "Fiber Transport" describes the dissemination of fibers from the burning composite, the possible atmospheric redissemination from the ground after deposition, and the penetration of building and electrical enclosures. "Vulnerability of Equipment and Shock Hazard" presents the sensitivity of equipment to carbon fiber from the standpoint of both equipment failure and potential shock hazard to individuals. "Facility Surveys" were performed to gather data required to bridge between laboratory and field experiments and the economic impact of electrical incidents attributable to fire-released fibers. "Risk Assessment" includes the development of suitable statistical approaches as well as appropriate evaluation of the sensitivities and implications of the various assumptions required.

FIBER SOURCE

An important element of carbon fiber risk assessment is the prediction of carbon fiber release from the crash and subsequent burning of commercial aircraft having structural parts made of carbon fiber composites. At the start of this investigation, no useful information on carbon fiber release was available from actual aircraft crash experience. However, the crash and burning of military aircraft with boron-epoxy parts and with carbon composite parts had generated free boron and carbon fibers. Thus the potential for carbon fiber release had been qualitatively demonstrated. Consequently, an extensive testing study was begun to provide experimental data needed to predict the amounts and characteristics of carbon fibers released from burning composites. The extent to which carbon fiber might be used in the structures of civil aircraft and be involved in fires by 1993 was also estimated.

Characteristics of Composites

Structural composite materials are generally multi-ply laminates of fibers embedded in a polymeric matrix material. Individual plies are cut to prescribed dimensions from tapes or broad goods and assembled with each ply oriented in the desired direction to provide specific strength and stiffness properties. The multi-ply laminate is cured by exposure to elevated temperature and pressure to produce a finished composite structure which has significant advantages over aluminum structure in terms of strength, stiffness, and weight.

Carbon fiber characteristics.- Carbon-based fibers, interchangeably referred to as graphite or carbon fibers, have high strength and stiffness that make them very attractive as the fibrous component of a composite material. Families of carbon fibers have been produced from a variety of precursor materials such as rayon, polyacrylonitrile, and

pitch. Moduli of elasticity of carbon fibers within these families range from 207 to 690 gigapascals (30 to 100 × 10^6 pounds per square inch) depending on processing parameters and precursor. In general, the higher modulus fibers have lower electrical resistance as shown in figure 4. Both trends are attributable to the higher degree of

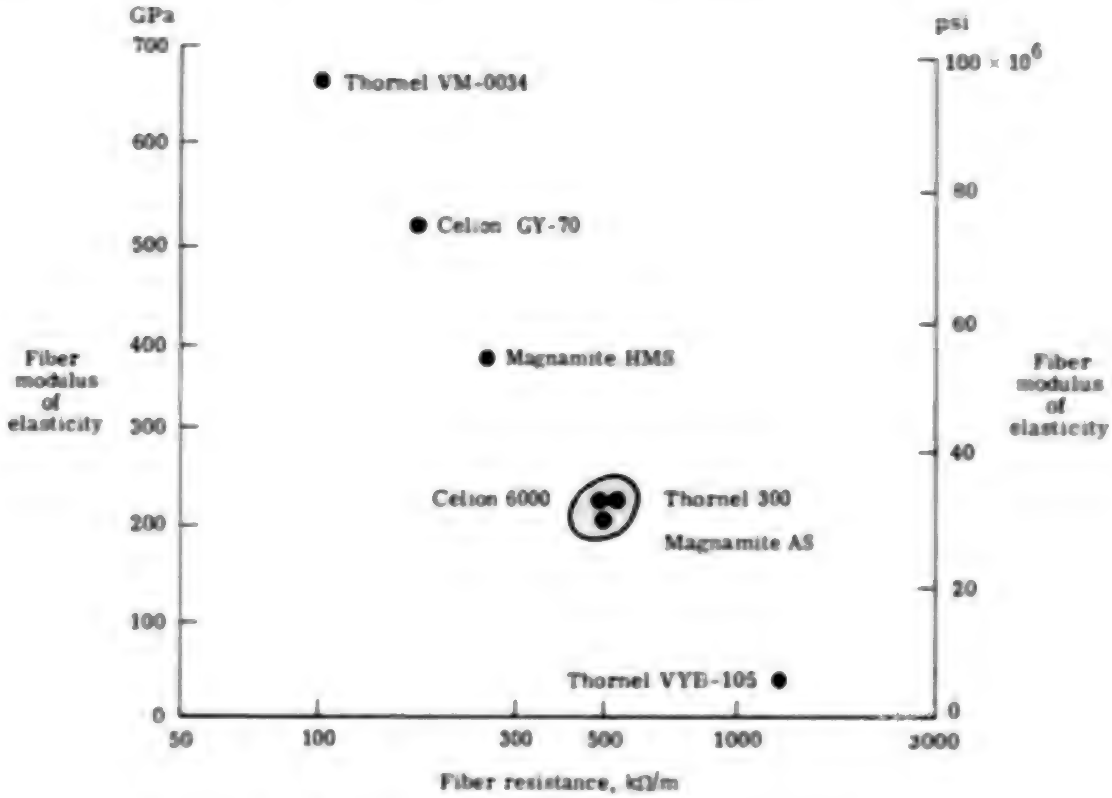

Figure 4.- Relationship between modulus of elasticity and electrical resistance of carbon fibers.

graphitization in these fibers during processing. Requirements for strength and damage tolerance in aircraft structures have led to the use of Thornel[1] 300, Magnamite[2] AS, and Celion[3] 6000 carbon fibers shown in the shaded area of the figure.

Matrix characteristics.- Structural composite material consists of fibers embedded in a matrix material. Although there are a variety of matrix materials for specific applications, epoxy matrices are commonly used in aircraft structural composites. Epoxies are highly cross-linked, high-molecular-weight, organic polymers that are generally cured at temperatures up to 475 K. They are not generally used where service temperatures exceed 360 K.

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[1]Thornel: trademark of Union Carbide Corp.

[2]Magnamite: trademark of Hercules, Inc.

[3]Celion: trademark of Celanese Corp.

Epoxies exposed to temperatures from 1200 to 1300 K associated with aircraft accident fires are nearly consumed in a few minutes. Although new polymers are being sought which have improved mechanical damage tolerance, environmental resistance, and manufacturing processibility, no organic polymer is expected to survive temperatures of jet-fuel fires.

Composite Usage Projections on Civil Aircraft

The number of applications of composite materials is increasing because of their superior structural performance. The current and projected applications include sporting goods, industrial equipment, automobiles, aircraft, and spacecraft. NASA has conducted and sponsored extensive research and development of composite materials applied to civil aircraft structures. Three major airframe manufacturers have produced components, evaluated them in service (ref. 6), and studied designs with 100 percent carbon composite wings and fuselages. Recently, one manufacturer decided to produce most control surfaces, fairings, and engine nacelles with carbon composites in the next generation of commercial airplanes (ref. 6).

The manufacturers of commercial aircraft calculated the weight of carbon composite currently envisaged for each aircraft series to be built through 1993. This information along with manufacturer and Federal Aviation Administration estimates of fleet size, fleet mix, and airplane retirements was used to predict the distribution of carbon composite on the fleet of commercial airplanes in 1993. Figure 5 is a graphic representation of these

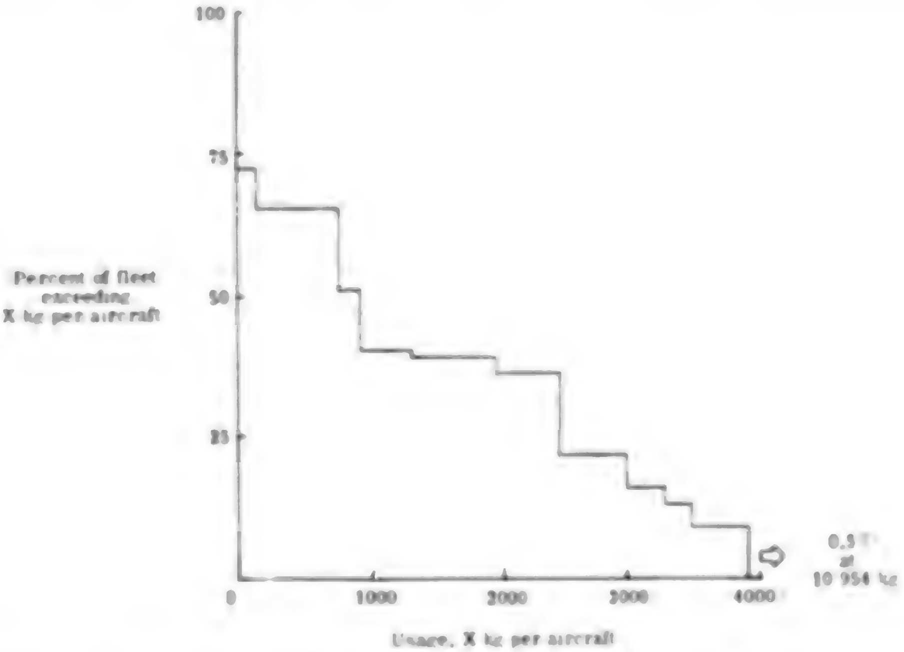

Figure 5.- 1993 projection of carbon fiber usage in commercial fleet.

data. In 1993, about 73 percent of commercial aircraft are expected to carry at least some carbon composites and 0.5 percent of the fleet to carry as much as 10 954 kilograms of carbon fiber per aircraft. This represents up to 10 percent of the airframe mass.

Figure 6 projects the amount of carbon fiber in service for commercial and general aviation aircraft from 1980 through 1993. The projection for commercial transport

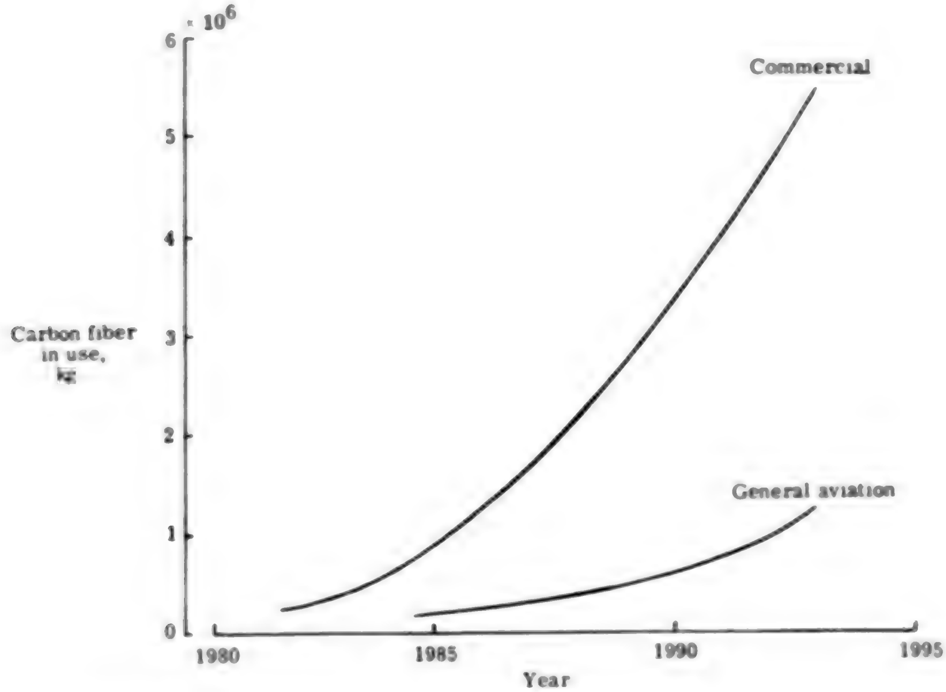

Figure 6.- Projected usage of carbon fibers in civil aircraft.

aircraft is based on data similar to those shown in figure 5 combined with fleet size. The projection for general aviation aircraft (which includes all other fixed and rotary wing aircraft) was based on 1978 usage increased at the rate (30 percent) projected for commercial aircraft. In 1978, there were one ongoing and two planned carbon fiber applications to general aviation aircraft.

Crash Fire Environment

Commercial aircraft accident records compiled by the National Transportation Safety Board and by manufacturers were analyzed (refs. 7 and 8) to determine the extent of fire damage to jet transports which have been involved in crashes since jets were first introduced. The results of the study provided the relationships among such critical aspects of crash fires as the phase of the aircraft operation, the percentage of structural

components involved in the fire, and the amount of fire damage. The frequency and extent of component fire damage in accidents with fires, shown in figure 7, are typical of data

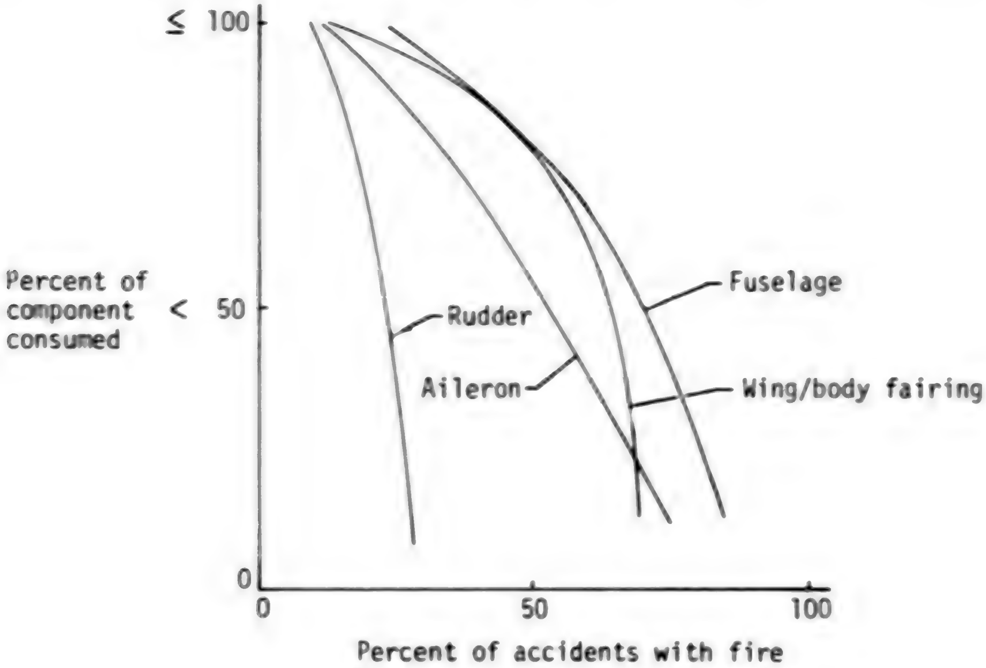

Figure 7.- Frequency and extent of fire damage to four aircraft components.

gathered in the study. For example, the rudder tends to be the least damaged component, while the fuselage is usually the most extensively damaged. The extent of damage by fire to composite parts was assumed to be equal to damage to the aluminum alloy parts covered in this study. Further, the expected expansion of the total civil fleet was assumed to be just balanced by improvements in safety. Thus, the number of fire accidents and the structural mass lost annually by fire were assumed to be constant. Commercial aircraft crash fires are sometimes accompanied by explosions, and this effect was also evaluated. Calculations based on these assumptions determined the amount of carbon fiber composite burned and, thus, the amount of fiber released from the simulated accidents upon which the risk assessments were based.

Fiber-Release Tests

Improved knowledge of the fire environment was essential to predict the fire temperatures, air and fuel concentrations, and flame velocities. These quantities were useful for making estimates of quantities and rates of matrix resin consumption, the amount of carbon fiber oxidation, and the amount and character of carbon fibers released into the atmosphere.

Composite material was deliberately burned and the products were analyzed to determine the number and sizes of released carbon fibers. Nearly 300 of these tests were conducted at several locations and ranged from small laboratory experiments (ref. 9) to large-scale outdoor simulations (refs. 10 and 11).

Combustion studies.- A set of preliminary fire and fire-plume calculations were made based on the best models and data available at that time. Atmospheric parameters, fire sizes, and fuel quantities were covered by the calculations. The study led to understanding the uncertainties of the models. The uncertainties then formed the basis for a series of outdoor tests (ref. 12) and further analyses (refs. 13 and 14) to better characterize combustion dynamics. The experimental tests involved outdoor JP-4 jet-fuel pool fires (fig. 8). Instruments on overhead cables measured temperatures, flame velocities, and gas species in the fires. The data from these fire tests were useful for refining the mathematical models (ref. 15) which guided the design of tests in which composites were burned.

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Figure 8.- Jet-fuel pool-fire test.

Laboratory fiber-release tests.- The laboratory fiber-release tests (refs. 16 to 20) were conducted in closed chambers. Small samples (up to 0.1 square meter in area) of composite materials were burned with a gas burner. The test samples were generally either flat composite plates or small specimens cut from prototype composite aircraft structural components. A variety of disturbances – air currents, compressed gas blasts, mechanical impacts, or small explosions – were applied to the fibrous residue after the matrix had burned.

This portion of the carbon-fiber-source study concentrated on observing and characterizing single carbon fibers released during fire tests. Because of their buoyancy, single fibers were expected to be disseminated most widely, to readily penetrate the filters and cases of electrical and electronic equipment, to damage more equipment, and, thus, cause greater economic loss than would larger fragments. Electrical vulnerability experiments, discussed later, indicated that fibers less than 1 millimeter in length would not contribute significantly to the electrical problem. Accordingly, most of the fiber-release data gathered were for single fibers over 1 millimeter in length.

Most single-fiber data were gathered from rectangular sheets of clear adhesive-coated plastic film onto which fire-released fibers settled as they fell in the vicinity of the fire tests. The individual fibers on the adhesive film were then laboriously measured and counted by various optical microscopic techniques (refs. 21 and 22). As the risk analysis program progressed, special techniques and instruments (refs. 23, 24, and 25) were developed to automate or otherwise simplify the fiber-counting procedure.

The laboratory tests addressed the effects of the following variables on the amount and characteristics of carbon fibers released from burned composites:

Nature of fire (fuel-rich, fuel-poor)

Duration of fire

Disturbances to residue during and after fire

Composite thickness and configuration (cross-ply, woven, unidirectional)

Composite surface and edge effects

Types of composite materials (fibers, resins)

Composite quality

Large-scale aviation jet-fuel fire tests.- The tests previously described were all conducted with propane or natural gas as the fuel in order to provide a clean atmosphere and avoid excessive contamination of the laboratory test chambers. However, uncertainties remained as to how representative the carbon fibers were of those which would be released in a jet-fuel fire resulting from an aircraft accident. Also, equipment

vulnerability assessments made with mechanically chopped, unburned virgin carbon fiber required verification by equipment exposure to carbon fibers released in a jet-fuel fire. Therefore, two types of jet-fuel fire tests were developed to characterize fiber release from representative crash fires and to expose equipment to such fibers. In one type, the effluent from carbon fiber composite burned in a jet-fuel fire was ducted through a long, large-diameter tube past a group of operating electronic units. In other tests, carbon-fiber-composite aircraft components were burned in a fire above the surface of a large outdoor pool of jet fuel with various types of instrumentation overhead and downwind to sample the effluent and its fallout to determine fiber-release characteristics.

A part of a large steel shock-tube structure (fig. 9) was modified to burn carbon fiber composites in a jet-fuel fire (ref. 11). The fire was ignited inside the tube midway

U.S. Navy photograph

Figure 9.- Shock-tube fire test facility.

along its length. The fire-released fibers, combustion products, and heated air were transported approximately 270 meters through the tube by exhaust fans installed in the large end. Samplers monitored quantities and sizes of carbon fibers released by the fire. Electronic equipment was exposed in the tube near the exhaust end.

Outdoor pool-fire tests were conducted (refs. 3, 10, 26, 27, and 28) in which composite structural parts having aggregate masses of 45 kilograms or more per test were burned. Pool diameter (10.7 meters) and length of burn (20 minutes) were chosen to simulate a representative aircraft fire. Tests were conducted when weather conditions and wind directions ensured maximum likelihood of accumulating the desired data. The efflux of carbon fibers was monitored in several ways. Fibers were collected just above the flames by an overhead array of samplers (ref. 29) and about 60 meters downwind by a vertical array. A huge Jacob's ladder (305 meters square) was supported by two barrage balloons about 140 meters downwind of the fire (fig. 10). It supported numerous samplers

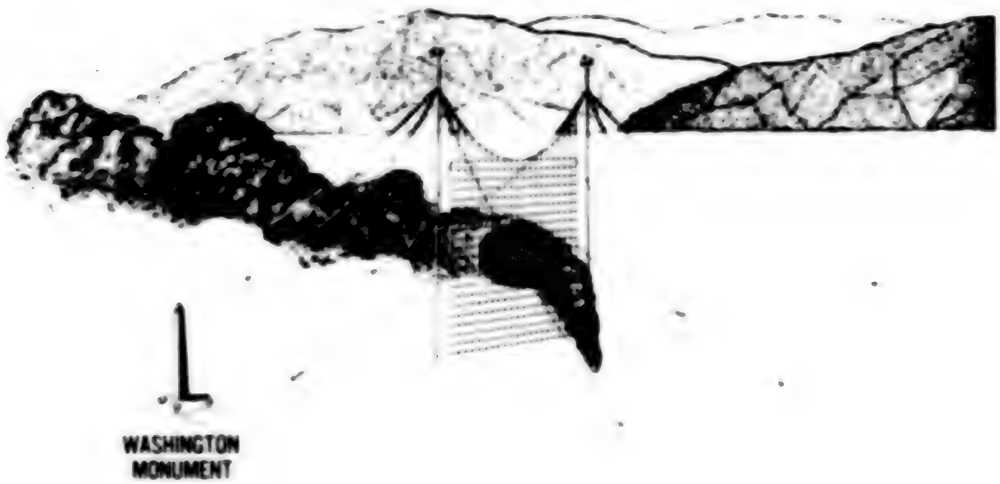


Figure 10.- Balloon-supported Jacob's-ladder net for sampling the fire plume.

to monitor quantities and sizes of fibers. Over 1300 passive samplers were mounted about 0.5 meter above ground in a fan-shaped array extending 19 kilometers downwind of the fire to measure fiber dissemination (refs. 28 and 30). In addition, strips and larger fragments released and deposited as far as 1 kilometer from the fire were collected by search teams and weighed for mass-balance accounting.

Results

The most important results of these experimental and analytical studies are summarized on the following pages. The supporting references document details of the tests and additional results.

Classification of debris.- In almost all tests, fibers were found with characteristics depicted in figure 11. Of special interest to this study were single fibers whose low fall

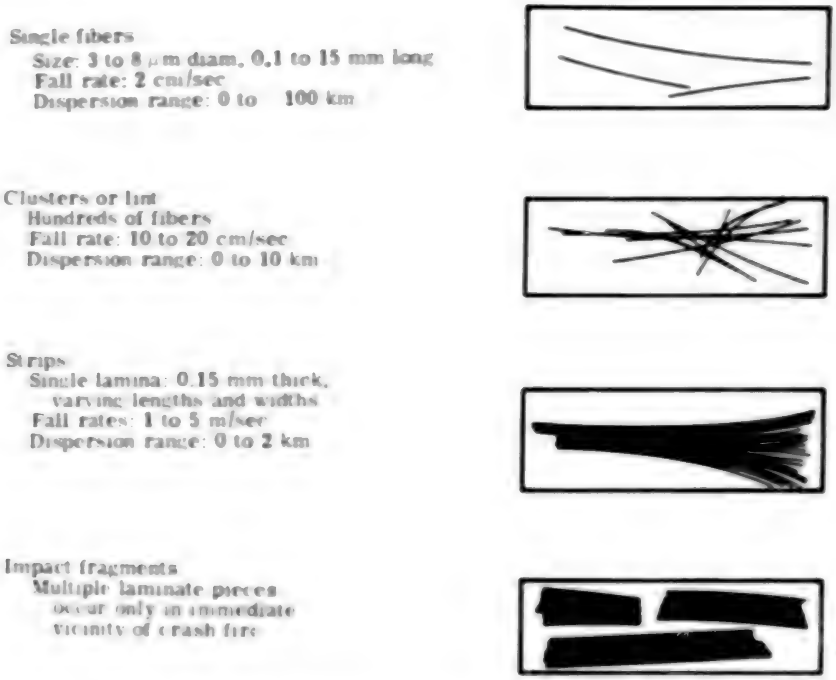


Figure 11.- Airborne fire-released carbon fibers.

velocity led to their dispersion over broad areas. Groups of fibers loosely bound in clusters fell faster and were dispersed over smaller areas. One-lamina-thick strips of fibers, bound together by incompletely burned resin or by the char formed when resin burned, were dispersed over even smaller areas. Still larger fragments, varying in size and shape, were usually produced only when the burning or burnt debris was mechanically disturbed. Because of their mass, they were rarely found beyond the immediate vicinity of the fire.

A fifth category of residue is shown in figure 12. The debris in the photograph was left after a 20-minute outdoor burn of stabilizers from a fighter aircraft. A large part of the structure remained in an identifiable shape in spite of major delaminations, oxidation of most matrix resin, and the release of fibers. In the foreground are a large number of strips described earlier. (The expanded wire mesh on which the man is standing was the test stand that had supported the stabilizers about 2 meters above the ground but had collapsed during the fire.)

U.S. Army photograph

Figure 12.- Carbon fiber residue from burned aircraft stabilizers.

Mass balance.- To the extent possible, debris of all these forms was statistically sampled, gathered, weighed, and summed to account for all fiber present in the experiment. Typical results from jet-fuel fire tests (refs. 10, 11, 26, 27, 28, and 31) are shown in figure 13. Between 15 and 60 percent of the original mass remained in place after the fire, except for the test in the shock tube. In the shock-tube test, the composite was burned in a wire basket that rotated about a horizontal axis to tumble the parts until all residue had been dispersed. Identifiable strips or fragments accounted for a significant portion of the original mass in many of the tests. The fiber samplers employed in these tests were designed and positioned to give a statistically reliable estimate of the single fibers (longer than 1 millimeter) released. For purposes of this calculation, only the lengths of fibers were considered; no mass adjustment was made for carbon consumed from the surface of counted fibers. Even so, single fibers accounted for only 0.2 to 0.6 percent of the fiber originally available (0.14 to 0.42 percent of original composite mass) except for the shock-tube test where single fibers accounted for 0.75 percent of the fiber originally available. The mass of fiber clumps was approximately equal to that of the single fibers. This left between 40 and 80 percent of the original mass not specifically accounted for. Of the 40 to 80 percent, most of the epoxy matrix was

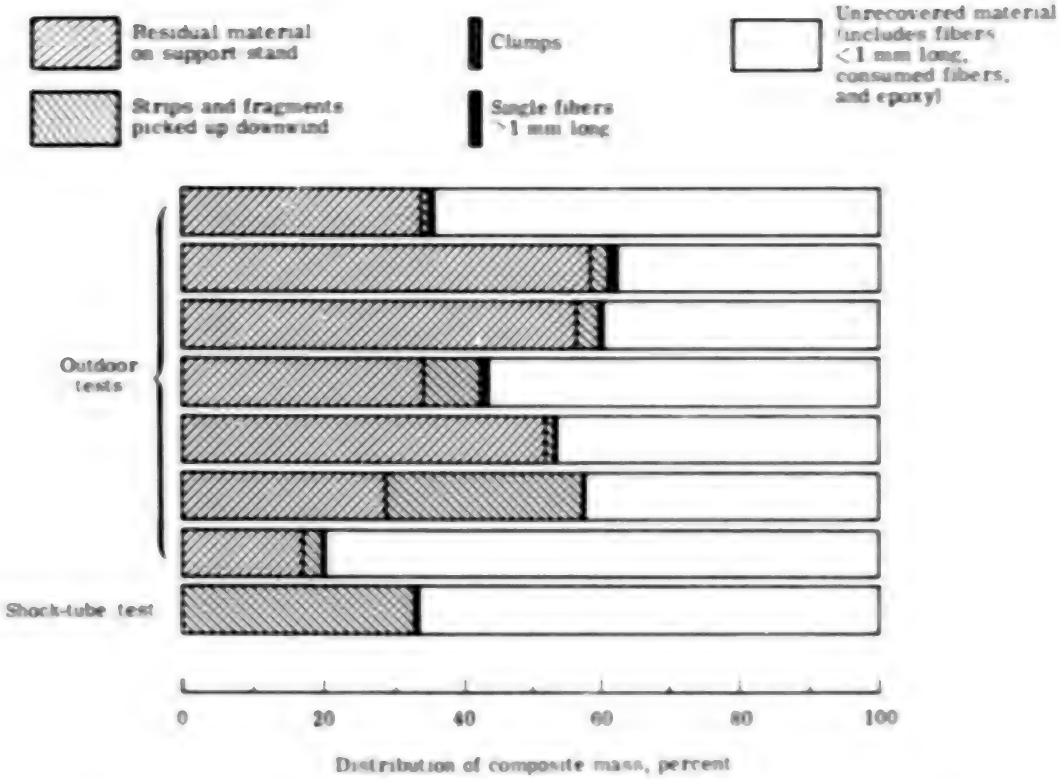


Figure 13.- Mass balance analysis of the composite materials burned in aviation jet-fuel fire tests.

consumed by oxidation which accounts for about 30 percent of the original mass. Also, the search teams may have missed some small fragments on the ground. The remainder of the unrecovered material is carbon fiber that was oxidized in the fire. Substantial fiber oxidation in fires had been predicted on the basis of laboratory thermogravimetric analysis coupled with fire plume dynamics and chemistry studies (ref. 9).

These observations confirmed earlier laboratory tests in which composites were burned until they were severely damaged and were subjected to mechanical agitation, airstreams, and explosives. Typical results from a large number of tests are plotted in figure 14. Single fibers accounted for less than 0.1 percent of the original fiber mass available when the composite was burned without disturbance. When tests included agitation of the debris by falling masses or gentle breezes, single fibers accounted for 0.001 to 1 percent of the original fiber mass available. Only when nearly sonic air blasts or explosives agitated the debris did single fibers account for more than 1 percent of the original fiber mass.

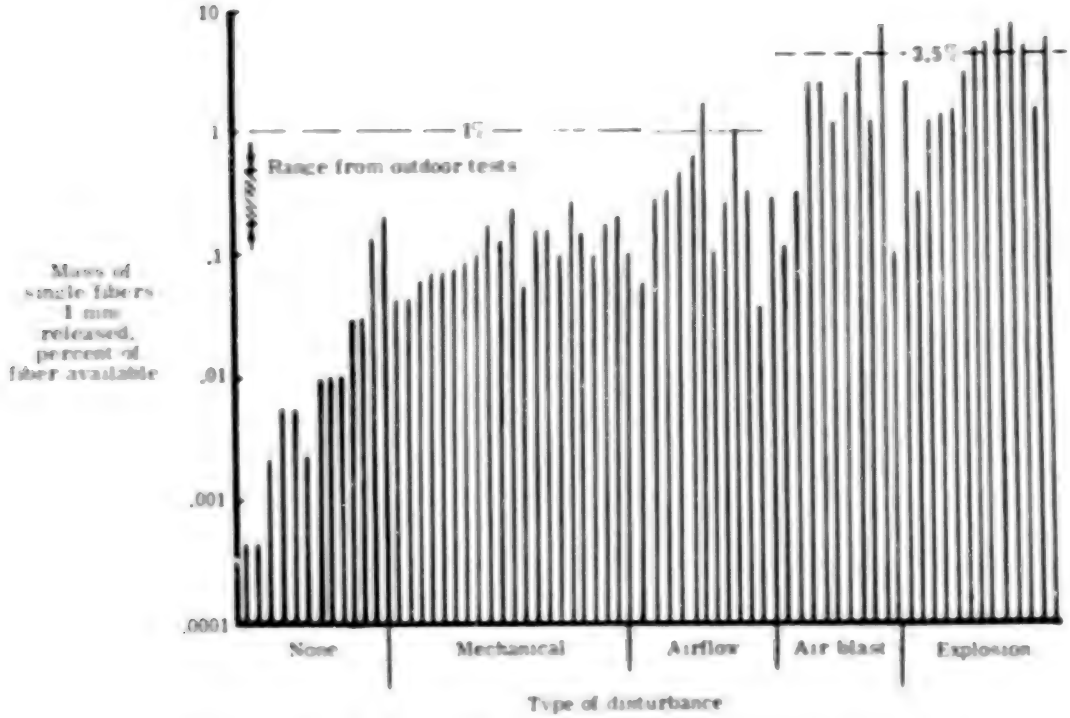


Figure 14.- Results of laboratory fiber-release tests.

The horizontal dotted lines in figure 14 show the values of 1 and 3.5 percent, which were chosen to represent the upper bounds of these data in the risk assessment. For those aircraft crash fires that involved no explosion, 1 percent of the originally available fiber in the burned composite was assumed to be released as single fibers longer than 1 millimeter. In the remaining crash fires, explosions were involved and 3.5 percent of the available fiber was assumed to be released.

Fiber-release rate.- The rate of single-fiber release was determined in three outdoor tests by active sensors hung on the Jacob's ladder. Recordings from these instruments indicated essentially a constant rate of release of single fibers through the duration of the fire. A typical cumulative history of fibers passing one sensor is shown in figure 15. The initial delay in sensing fibers was the time required for fibers to be released from the matrix and be transported to the sensor. As the fire went out after 20 minutes, the rate of fibers passing the sensor dropped to zero.

Length of fibers.- Single fibers observed in these studies were much shorter than originally expected. To assess electrical risk, only those fibers longer than 1 millimeter

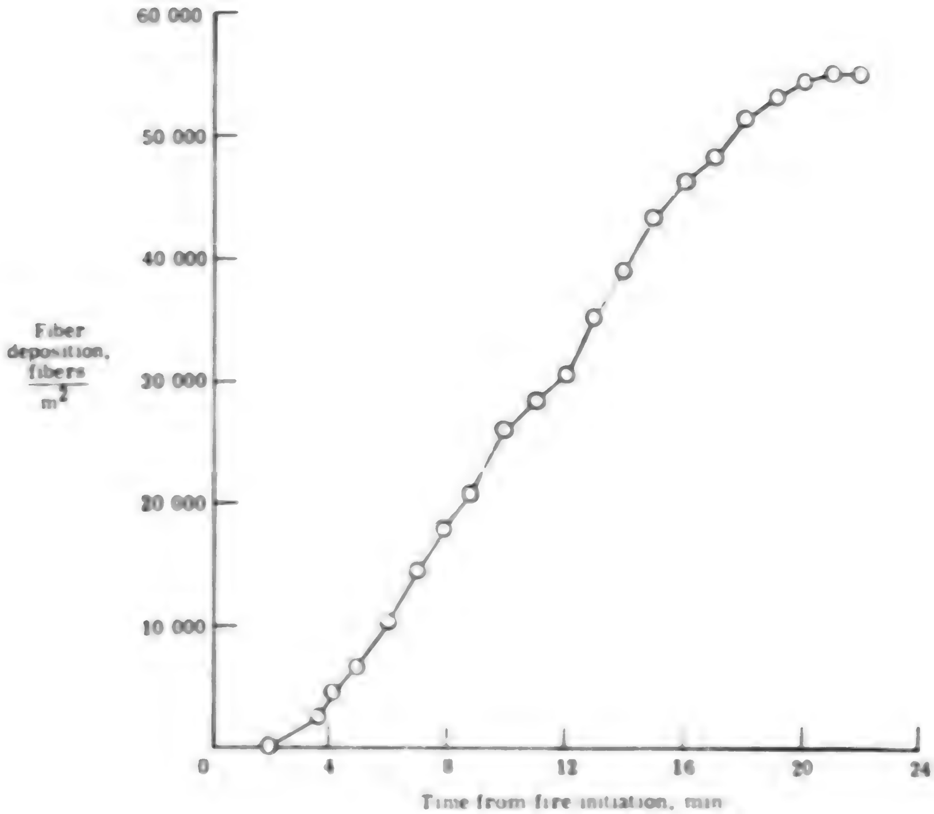
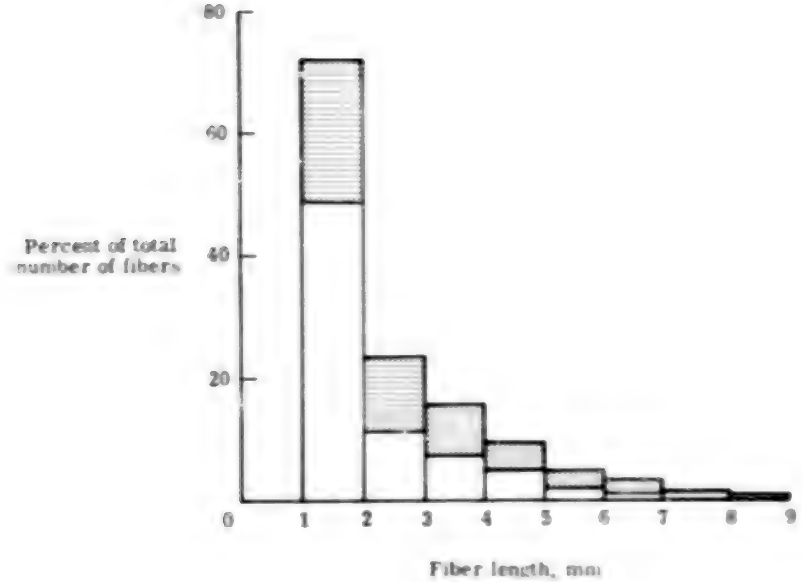


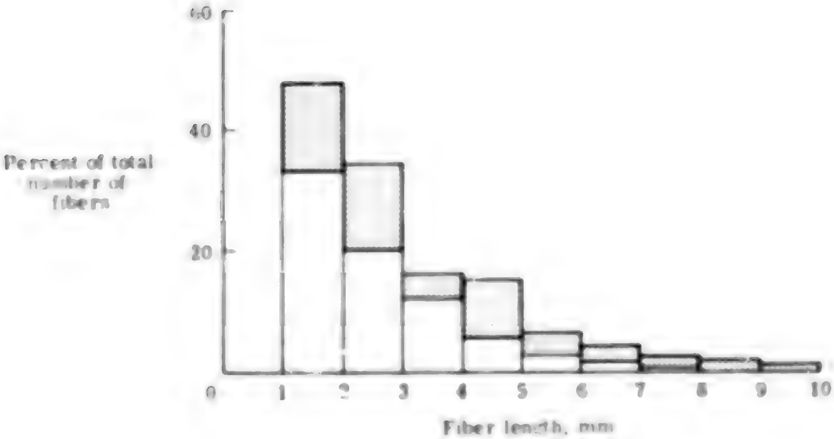
Figure 15.- Cumulative history of fibers released during burning of composite components in a 20-minute aviation-jet-fuel fire.

were of interest. Their lengths were distributed as indicated in figure 16(a) for laboratory tests. The shaded portions of the figure represent the range of data taken in a large number of fire-release tests with and without significant agitation of the debris. A similar distribution of lengths (fig. 16(b)) was observed in seven outdoor tests. Considering the many variables in the tests, the agreement is excellent. Fiber-length distribution appears to be independent of test conditions. In each set of data, the preponderance of fibers were between 1 and 3 millimeters long, and very few fibers were longer than 4 millimeters. The mean length was between 2 and 3 millimeters. A 2-millimeter mean length is equivalent to 5×10^9 fibers per kilogram. This number was used in the risk assessment computations.

Investigation of fibers shorter than 1 millimeter (refs. 9 and 31) established that these shorter fibers constituted 67 to 74 mass percent of the total single fibers released by fires alone, and up to 98 mass percent of those released in fires accompanied by



(a) Released in laboratory tests. Shaded regions indicate ranges from tests with and without disturbance.



(b) Released in outdoor aviation-jet-fuel fire tests. Shaded regions indicate ranges for seven tests.

Figure 16.- Distributions of lengths of fibers longer than 1 mm.

explosions. The electron micrographs of burned fibers in figure 17 illustrate why short fibers were found. The long lengthwise markings are sites where the fiber had been

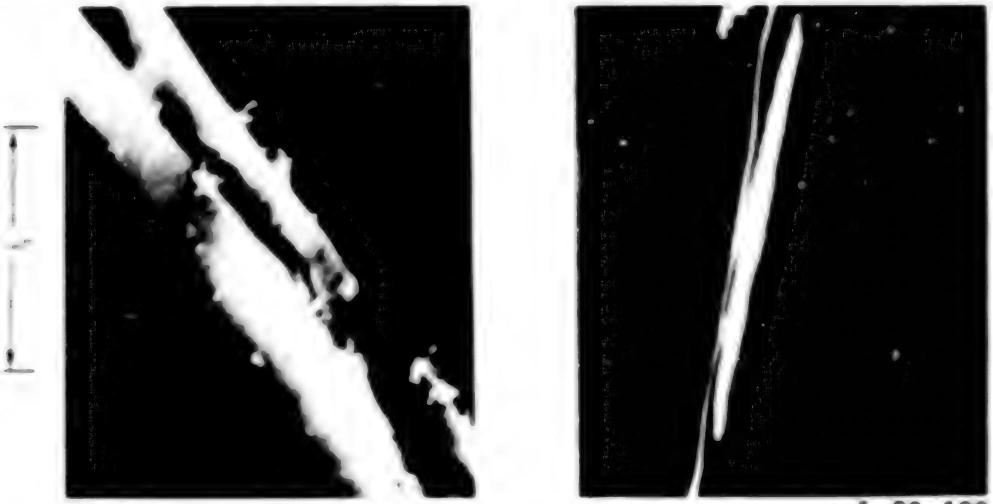


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Figure 17.- Photomicrographs of fire-oxidized fiber.

preferentially oxidized. The preferential attack made the fibers vulnerable to breakage by minor disturbances. This oxidation was aggravated because of relatively high concentrations of metallic ion impurities (e.g., sodium) sometimes present in the acrylic precursor to the carbon fibers (ref. 32).

Fiber diameters.- The phenomenon that led to short fibers almost always led to small fiber diameters. The diameters of sample fibers longer than 1 millimeter released in the seven outdoor tests were determined. The results are shown in figure 18. Clearly,

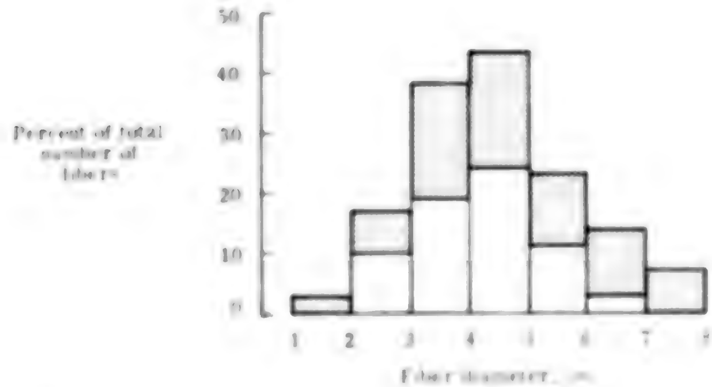

Figure 18.- Distribution of fiber diameters for fibers longer than 1 mm released in outdoor aviation-jet-fuel fire tests. Shaded regions indicate range of results for seven tests.

most diameters were reduced significantly from the original 7 micrometers. The mean diameters of these samples were 4.0 to 4.7 micrometers. The shaded portions of the figure represent the ranges of values observed.

The possible health considerations of fibers which were smaller than those of electrical concern led to a preliminary investigation which showed that 95 percent of the fire-released carbon fibers were less than 1 millimeter long. A more extensive study (ref. 32) was then conducted to assess the prevalence of fibers which were conservatively defined to be of potentially respirable size (less than 80 micrometers long, less than 3 micrometers in diameter, and with length-to-diameter ratios from 3:1 to 10:1). The results of that study disclosed that no more than 23 percent of the fibers released from jet-fuel fire tests fell in that size domain. As seen in figure 17, the overall fiber diameter had been reduced drastically from the original 7 micrometers to approximately 3 micrometers; and the splitting, or fibrillation, that seems imminent could reduce it further to approximately 1 micrometer. As indicated earlier, large portions of carbon fiber had been completely consumed by oxidation.

In the absence of any evidence that carbon fibers of any size could have adverse health effects on humans (except for typical cutaneous allergic reactions to many fibrous substances), comparisons were made with the quantities of concern in the case of other fibers. With the conditions and some of the results of one of the large-scale, outdoor jet-fuel fire tests as the scenario for an extreme-case aircraft crash fire, a maximum concentration of respirable-sized carbon fibers which was carried downwind in the densest part of the smoke plume was computed (ref. 32). A concentration of 5×10^6 fibers per cubic meter was found for a point close to the fire. The total exposure to carbon fibers from that extreme-case accidental crash fire was predicted to be less than 0.5 percent of the maximum occupational exposure recommended by the National Institute for Occupational Safety and Health (NIOSH) for exposure in a 10-hour workshift to respirable-sized fibrous glass or other man-made fibers.

Field tests conducted during the outdoor tests showed lower values than had been calculated for the extreme case in reference 32. The actual total exposure of potentially respirable fibers 140 meters from the fire for the entire test was less than 0.16 percent of the NIOSH limit recommended for 10-hour exposure to fibrous glass fibers.

This combination of computed and experimental data for potentially respirable fire-released carbon fibers indicated that low quantities are released from burning aircraft composite structural parts, and these fibers are not known to have adverse physiological effects on humans.

Electrical resistance.- Measurement of electrical resistance of fire-released fibers of different diameters indicates that fiber resistance varies approximately as the inverse of the cross-sectional area of the fiber (refs. 11 and 25).[4]

FIBER TRANSPORT

Four separate topics relating to fiber transport were investigated:

- Plume rise: how do the fibers released during the fire rise with the buoyant gases?
- Dissemination: how does the cloud of fibers disperse in the atmosphere and finally settle?
- Resuspension: how are once-deposited fibers picked up by air currents at a later time?
- Transfer: how do fibers enter buildings and enclosures to reach electrical equipment?

These four topics are common to many pollution problems and, in most instances, this study adapted existing models to the present problem and determined specific fiber-related parameters for the existing models.

Plume Rise

The study assumed that single fibers would be freed from the burning composite parts and rise with the combustion products. The model developed by Briggs (ref. 33) for the rise of hot gases from smokestacks was used to calculate the height to which the fiber cloud would be lofted. This model uses the fuel burning rate and the atmospheric conditions to calculate a height at which the heat from the gases has been sufficiently diluted to make the cloud neutrally buoyant. For accident simulations involving explosion, the fibers were assumed to be released outside of the buoyant fiber plume and not lofted. That condition led to the most severe ground-level exposures.

Dissemination

Many mathematical models exist for the transport of particles in neutrally buoyant clouds. These models have been verified by comparison with a large data base from

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[4]The data on the resistance of burned fibers in reference 3 are incorrect because of a measurement technique error. The data and analyses of references 11 and 25 show that fire-released fibers have a higher resistance than was reported in reference 3.

pollution studies with gases such as industrial sulfur dioxide, with liquid droplets such as agricultural sprays, and with solid particles such as fly ash from smokestacks. Those models are based on the dispersion of the particles by natural turbulent mixing of the atmosphere. The only property of the pollutant particle considered in these models is the still-air fall velocity. The fall velocities for single carbon fibers 7 micrometers in diameter were measured and calculated (ref. 34) to be 20 to 30 millimeters per second. These values are in the range for which the existing dissemination models were developed and effective.

In most pollution problems, a threshold of exposure exists below which the effects of the pollutant can be ignored. Therefore, the existing models have been developed with emphasis on the accuracy of the peak values of contamination, and with less emphasis on the accuracy of the very low contamination very far downwind. Because the carbon fiber contamination problem may have no lower threshold of sensitivity, the dissemination models had to be evaluated to very low concentrations and, hence, to distances much beyond those to which they had been tested previously. Because an experimental evaluation appeared prohibitively difficult, an analytical approach (ref. 35) was used to ensure that the models were conservative over these large distances.

For the further detailed discussions of dissemination, the following terms and definitions are used:

- Concentration: The basic measure of particle pollution in terms of number of particles per unit volume; its symbol is C.
- Exposure: The integral of the concentration of particles over the time during which that concentration has an effect; its symbol is E and its units are fiber-sec/m^3.

$$E = \int C \, dt$$

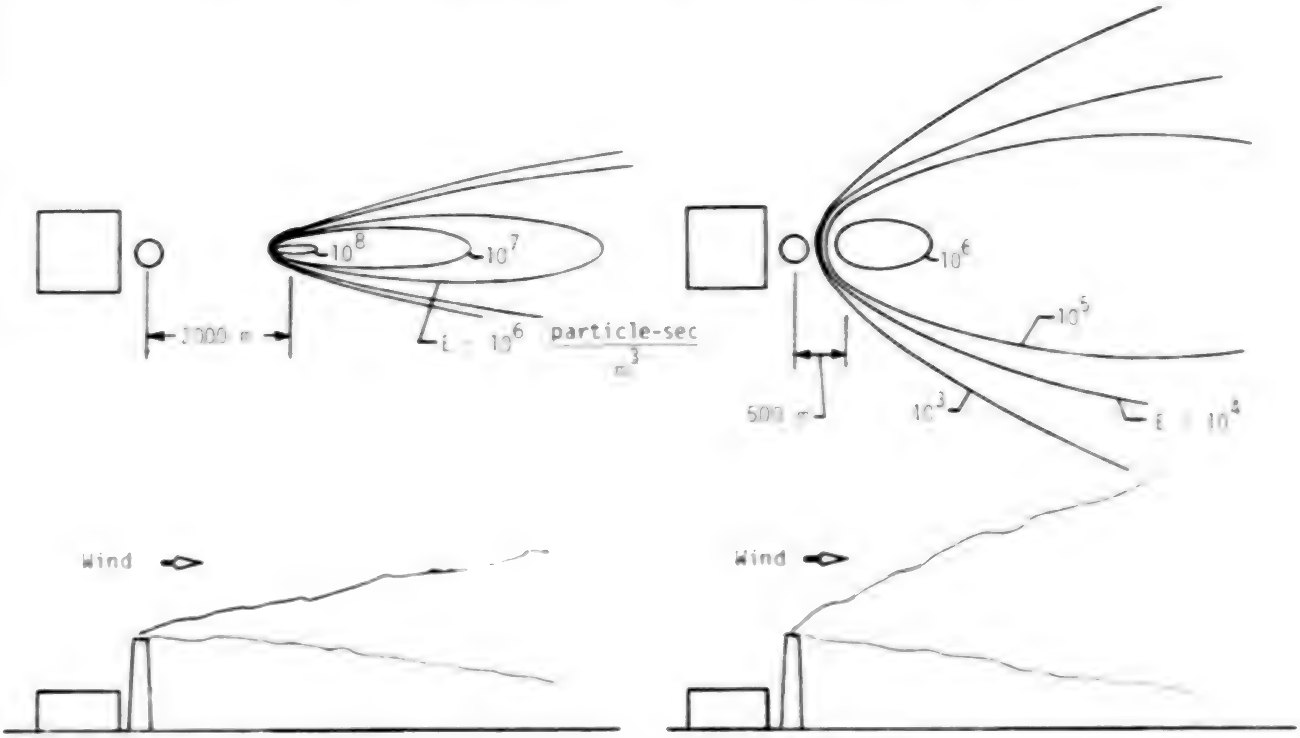
- Deposition density: The number of particles per unit area of horizontal flat surface; its symbol is D. The deposition at a point is the product of the total exposure at that point and the fiber fall velocity v_s; that is,

$$D = Ev_s$$

The dissemination models used in the risk assessment predict the expected exposure levels resulting from a known number of fibers released into the air. They are sensitive to meteorological conditions which determine the extent of turbulence in the atmosphere such as temperature gradients, insolation, and wind velocity. For these

models, all weather conditions have been divided into six categories ranging from stable, through neutral, to unstable (ref. 36).

Figure 19(a) illustrates a factory smoke plume in a nighttime stable atmosphere and the predicted exposure pattern for a release of 1 billion particles. Figure 19(b) shows a



(a) Stable atmosphere.

(b) Unstable atmosphere.

Figure 19.- Atmospheric dissemination and exposure (E) footprint for particles in a factory smoke plume.

similar event for a sunny day with light winds, a condition labeled unstable because air heated near the ground rises by convection through the higher air layers until it reaches an inversion layer. In unstable weather, the plume rises higher and disperses faster. The ground-level exposure pattern covers a larger area but the exposure values are lower than for the stable atmosphere. For each weather category, the models use an average spread angle for the cloud based on smoke-plume observations and a limiting height to which the cloud can rise.

Gaussian dissemination models (refs. 37 and 38) treat a pollution source as a point source growing in two dimensions such that the concentration profile is always a Gaussian distribution. That distribution represents a good estimate for plumes of long duration such as those from industrial smokestacks. However, there is much short-term variability in a fire plume. Thus, the Gaussian description should not be interpreted as a

real physical description, but rather as the average description for many similar short-term events under the same meteorological conditions. To account for the growth limitations set in the vertical direction by the inversion height and by the ground, a light-beam analogy is used to reflect the growing "beam" (the particle cloud) back inside the turbulent convection layer. The appropriateness of the Gaussian models and the light-beam analogy were analyzed (ref. 35). For short carbon fibers and their range of fall velocities, these models produced results which agreed very well with results from a much more complex full-diffusion analysis. Therefore, the risk calculations were made with these models.

For mathematical convenience, most dissemination models assume that all particles are released from a single point source. The height of the point source above the ground is an important variable in determining the location and strength of the maximum ground-level exposures. Figure 20 shows the exposure along the downwind centerline for two

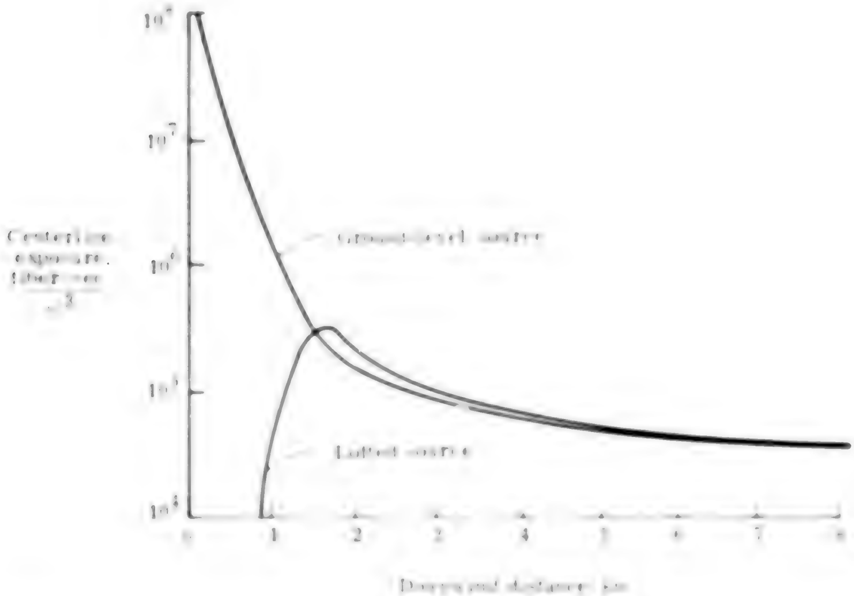


Figure 20.- Exposures from lofted and ground-level sources.

releases of 1 billion fibers each. In one example, the fibers are released by an explosion at ground level. The point-source calculation predicts singular behavior for the exposure at the release point but only a small wedge of ground area is exposed to these levels. In the other example, the fibers are lofted to 200 meters in a neutral atmosphere. The results differ greatly for the first 2 kilometers, but are essentially identical farther downwind. The integrated effect is small.

In the large-scale outdoor jet-fuel fire tests (refs. 10 and 28), the exposure measured showed that not all the fibers were lofted with the hot plume. The best agreement between test and theory was obtained with the assumption that only half the material was lofted with the fire plume and the other half was released at ground level. Similar results have been reported (ref. 39) for the fraction of smoke lofted with the fire plume. That study showed that an average of 40 percent of the smoke drifted downwind without any lofting. The risk analysis described in a later section did not account for this effect. However, in a sensitivity study, the risk from explosions releasing 3.5 percent of available fiber at ground level was three times the risk from fires releasing 1 percent of available fiber at the plume rise height. This ratio is roughly the ratio of fiber released and suggests that the height of the fiber source is not an important consideration in predicting total risk.

The relatively unimportant influence of plume height on total risk is further illustrated by recognition of one important invariant that relates all exposure distributions. Because the deposition in a small area dA is

$$D\,dA = v_s E\,dA$$

the total deposition over the whole area A on which particles can be distributed is

$$\int D\,dA = v_s \int E\,dA$$

This must be equal to all the fibers initially released, so that if N is that number of fibers,

$$N = v_s \int E\,dA$$

This area integral of exposure is a constant, dependent only on the number of fibers. If the fibers are uniformly dispersed over an area A, the product of the area covered and the exposure over the area is a constant

$$EA = N/v_s$$

Figure 21 is a plot of this interrelation between exposure and area for release of any given mass of fibers of 2-millimeter mean length. The dashed line shows that for the worst-case aviation accident postulated, the area of one typical suburb could be covered to an exposure of 5×10^6 fiber-sec/m^3, or that the area of a typical city could be covered to an exposure of 5×10^5 fiber-sec/m^3. These exposures are values outside buildings.

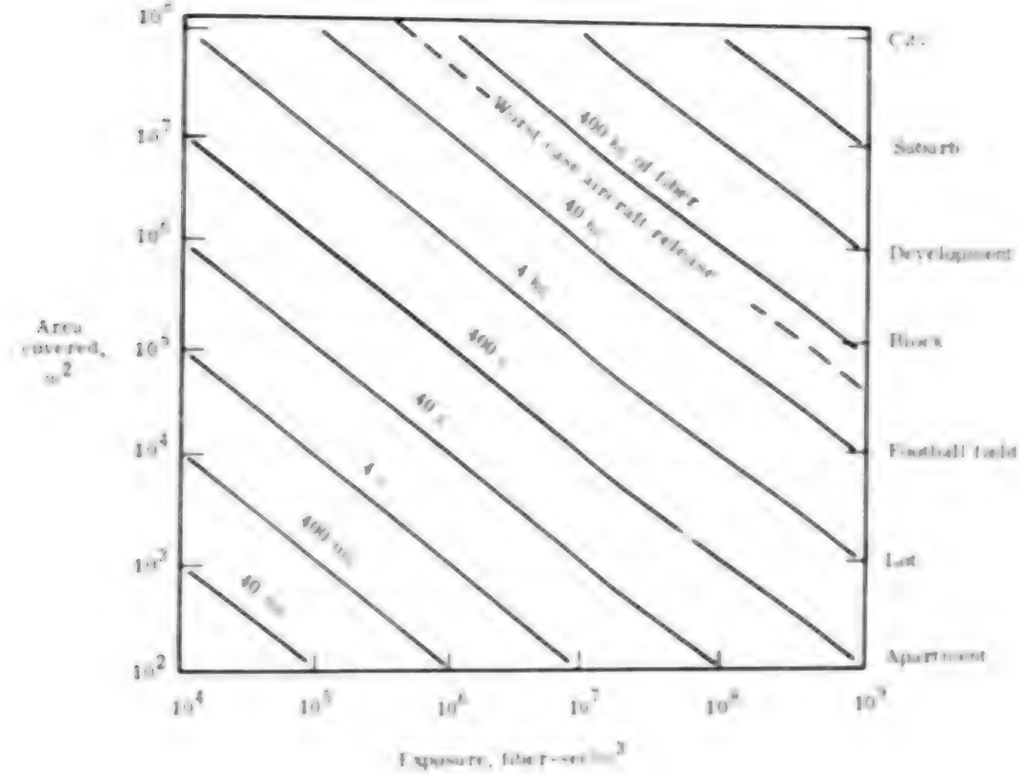


Figure 21.- Parametric plot of carbon fiber exposure distribution. Mean fiber length of 2 mm.

Resuspension

Resuspension of deposited particles is a phenomenon which occurs in dust and sand storms and has been studied to understand many pollution problems. But models applicable to sand and dust were considered unsuitable for carbon fibers because the aerodynamic characteristics of cylindrical fibers are quite different from those of more nearly spherical dust and sand. Therefore, a study was conducted to monitor the resuspension of carbon fibers from a desert area where about 50 kilograms of cut fibers had been deposited (ref. 40). The fiber flux from that area was monitored and analyzed at regular intervals for more than 3 years. As shown in figure 22, the initial rate of resuspension was highest, and very few fibers were being released from the area after 3 years. The total number calculated as having been resuspended was less than 1 percent of the number originally deposited. An analysis of the length of the airborne fibers shows that, after 3 years, only 1-millimeter fragments were being resuspended. The average length of the resuspended fiber is shown in figure 23.

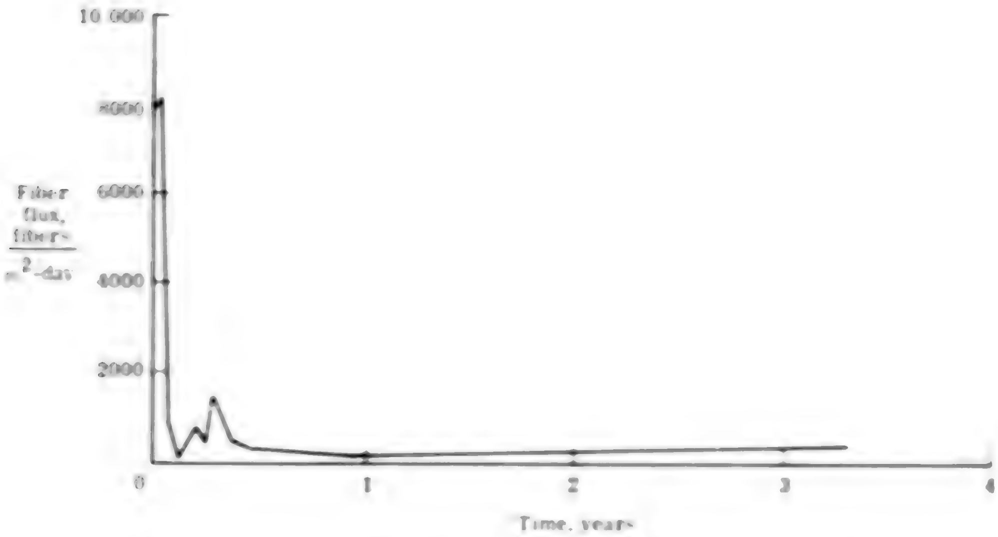


Figure 22.- Carbon fiber resuspension with time.

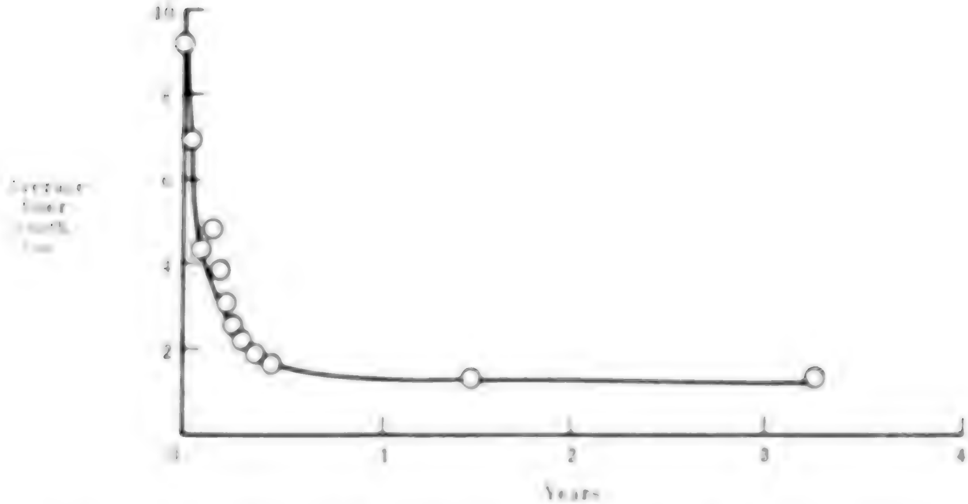


Figure 23.- Change in length of resuspended fibers with time.

An analysis of the desert surface showed that many fibers and fiber clumps had been washed into depressions and were covered with soil, while others had been trapped under the roots of desert vegetation. Other surfaces would presumably have different resuspension characteristics. Water, forest, and other high vegetation probably would suppress resuspension completely, while paved surfaces probably have high resuspension rates. However, washdown from rain would limit the time over which the material was available for resuspension from paved surfaces (ref. 41).

On the basis of these findings, the contribution to the exposure from resuspended particles was expected to be small compared with the original exposure. Therefore, the risk assessment was made without any contribution from resuspended particles.

Transfer

In this study, the fiber transfer function was defined as the ratio of exposure inside a building or enclosure to the exposure outside. The electrical and electronic equipment which is vulnerable to carbon fibers is seldom exposed outside of buildings. Instead, buildings, filters, and cabinets protect such equipment. The applicable transfer functions were studied to determine the degree of protection offered by such enclosures (ref. 25).

Airflow models were developed to determine the possible flow of fibers into buildings and to establish the transfer functions. These models indicated that airflow rates, filter factors, fiber fall velocity, building height, and floor area all influenced the transfer functions. Although airflow data for ventilation and leakage were available from building standards, filtration data through filters and screens had to be determined.

In experimental studies (refs. 25 and 42 to 44), the filter effectiveness for numerous filter types was established. Figure 24 shows an experimental correlation between the

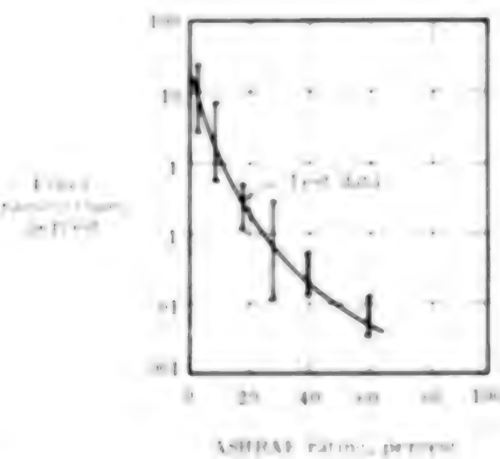


Figure 24.- Filter transmission for virgin fibers 3 mm long.

filter transmission factor and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Dust Spot Rating, a standard industrial rating system for filters. These data indicate that many industrial filters pass fewer than 10 percent of the fibers they encounter and some pass far fewer. Ordinary window screens were found to transfer only 10 percent of the 3-millimeter fibers striking them. Naturally,

the effectiveness was higher for fibers than for spherical particles of the same diameter, the normal rating basis for filters. Also, the filters were more effective at stopping long fibers than short fibers. As a result, the fiber-length distribution after filtration was relatively shorter than before filtration. The risk calculations ignored this effect and conservatively used the fiber-length distribution measured at the fiber source.

Analytical studies and experimental results showed that fibers break up in significant numbers when they impact surfaces at speeds near 50 meters per second in high-velocity air-handling equipment. Simulation tests (ref. 25) showed that only fiber dust could be expected to enter an aircraft air-conditioning system through the jet engine and intakes. Therefore, the in-flight transfer function for aircraft was assumed to be zero in the risk assessment.

VULNERABILITY OF EQUIPMENT AND SHOCK HAZARD

The vulnerability of electrical and electronic equipment to malfunction or damage when exposed to carbon fibers and the potential shock hazard were assessed in a systematic series of experiments. These experiments included

- Probing the circuitry with shunts of known resistance
- Exposing equipment to chopped virgin fibers in a closed chamber
- Exposing equipment to fire-released fibers

Over 150 pieces of equipment were tested, including household appliances, moderately complex electronics, and avionics. In addition, the attenuation effects of fibers on signals for airport landing aids were assessed analytically.

Because shock hazards were considered a potential threat to human life, many consumer devices were investigated for potential shock hazard (ref. 45). Of these, the toaster presented the most significant hazard. A plot of the results of tests with six toasters is shown in figure 25. These results were shown to produce less than 0.38 potential shocks per year (refs. 46 and 47). None of the potential shocks drew currents that would be considered lethal because the fiber would burn out before a dangerous level was reached. Therefore, the shock hazard was not considered further.

Test Methods

Tests with simulated fibers.- A wide range of household and other appliances were probed with a fiber simulator (ref. 45). The simulator was a hand-held probe (ref. 48) having a variable resistor to represent a carbon fiber. The control circuit for the probe measured the current flowing through the simulated fiber and simulated burning the fiber to evaluate whether a fiber-caused malfunction would persist. Consumer appliances

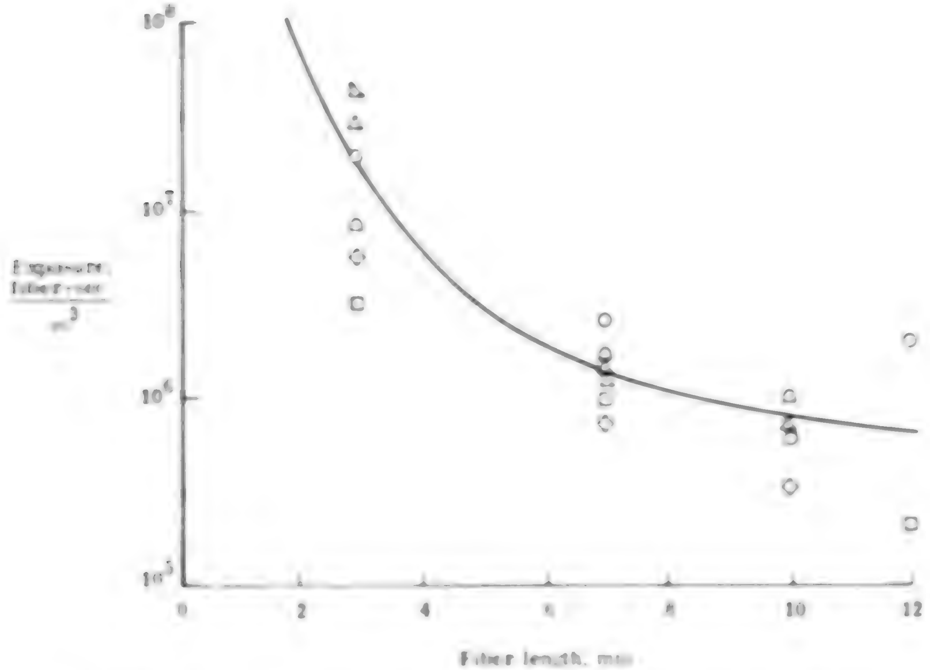


Figure 25.- Mean exposure required for short circuit to case of six toasters. Each test-point symbol represents a different manufacturer.

having electromechanical and simple electronic logic components with up to a few hundred potentially vulnerable pairs of contact points were quickly probed (ref. 45). The consumer equipment tested represented over 85 percent (total value basis) of the consumer goods in current use.

Tests with chopped fibers.- A somewhat more realistic, but more expensive, series of tests was conducted on similar appliances, but in a closed chamber into which chopped virgin fibers were blown. For most of these tests, Thornel 300 fibers were utilized because this fiber is representative of those used in aircraft structural composites. Fiber concentrations were approximately 10^3 fibers/m^3, a value that is higher than that experienced in the fire-release tests (ref. 10).

Equipment was exposed until failure or until an exposure of 10^8 fiber-sec/m^3 was achieved. This exposure deposited essentially a continuous mat of fibers on the floor of the test chamber. Although large exposures were needed to evaluate the mean exposure to failure $\bar{E}$, exposures larger than 10^3 fiber-sec/m^3 would seldom be experienced as a result of an aircraft accident.

The fibers were chopped to uniform lengths for each test, but the length was varied from 1 to 20 millimeters, the range of fiber lengths expected to be significant contributors to electrical risk.

The electrical devices under test were usually powered during the exposure, but some devices were exposed with no power to study potential failures caused by previously deposited fibers. If the devices under test were equipped with forced ventilation or were convectively cooled, these features were allowed to function as they would in a service environment. For some tests of avionic equipment, a noise and vibration environment was imposed to further simulate service conditions.

One of the test chambers used (refs. 47 to 51) is sketched in figure 26. Generally, the tests were performed with fibers falling freely in still air.

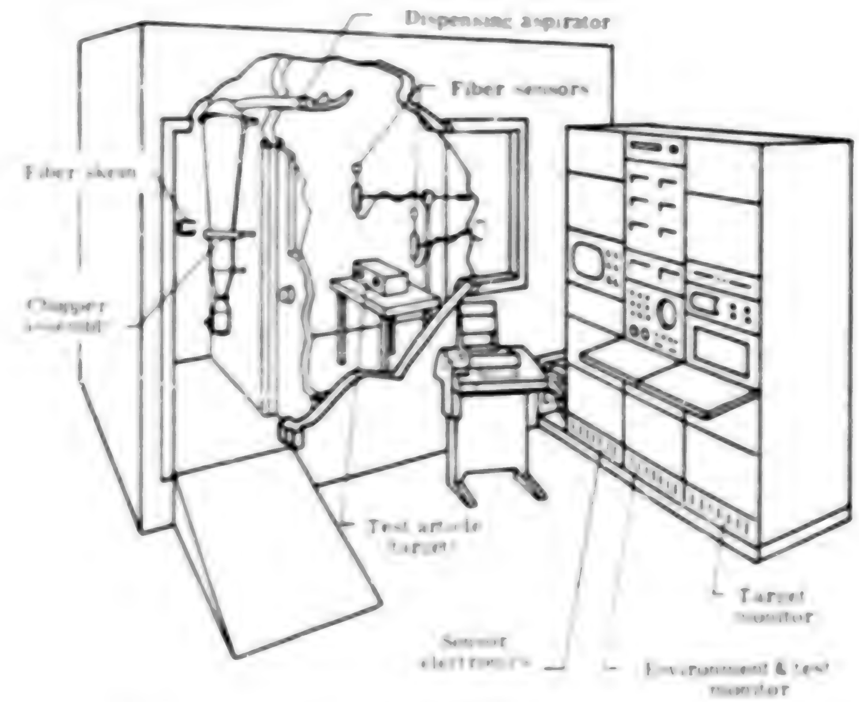


Figure 26.- NASA carbon fiber test chamber.

Tests with fire-released fibers.- Additional tests (ref. 11) were performed with six stereo amplifiers exposed to carbon fibers released by burning composite components in a pool fire of JP-1 fuel. The fire plume was enclosed in a horizontal tube about 6 meters in diameter which conducted it to a test section in which the electronics and test instrumentation were installed. Some of the tests were made without fibers to study whether failures were induced by the soot or heat.

Results of Fiber Exposure Tests

In general, the equipment was less vulnerable than had been expected (refs. 3, 11, 25, 45, 47, and 49 to 52). In almost all cases, the equipment was restored by vacuuming the affected circuitry.

The results of tests performed on stereo amplifiers are shown in figure 27. The vulnerability predicted from chamber tests using virgin fibers (ref. 50) was almost

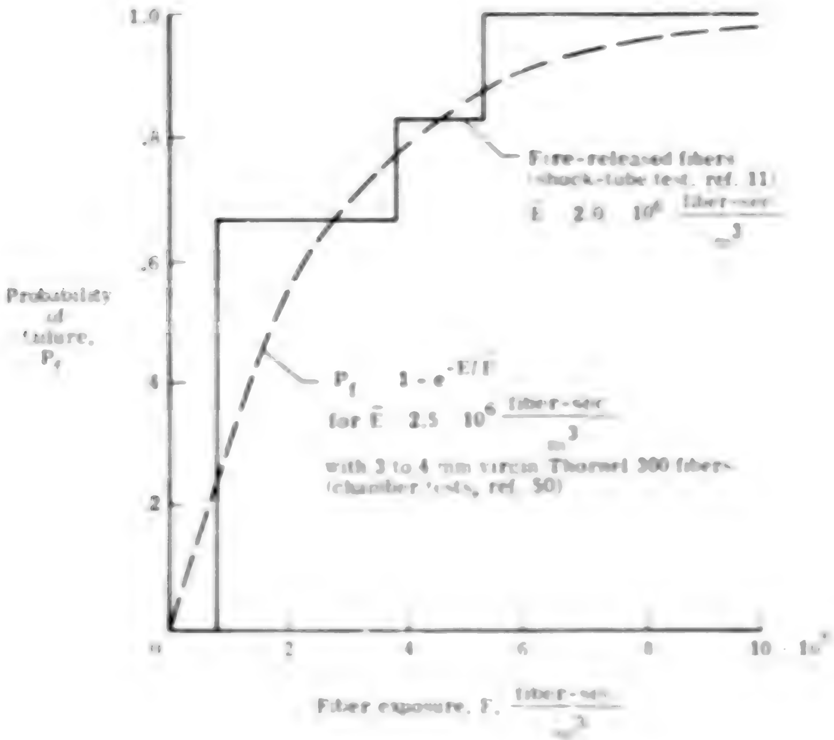


Figure 27.- Failure of stereo amplifiers caused by exposure to carbon fibers.

exactly reproduced in the fire-released fiber tests (ref. 11). Therefore the chamber tests were considered suitable for assessing vulnerability of specific equipment. The effect of increased fiber resistance (associated with the decrease in cross section of oxidized, fire-released fibers (refs. 11 and 25)) was not evident from the fire-released fiber test results. This effect should raise the mean exposure to failure $\bar{E}$ for equipment exposed to fire-released fibers over that predicted from chamber tests, and thus conservatism to the vulnerability predictions (ref. 25).

The following generalized comments characterize the vulnerabilities observed for each of several categories of equipment.

Low-voltage equipment (0 to 15 volts) was susceptible to failures if fibers could reach critical circuitry. However, many devices had few vulnerable contacts and others were well protected against penetration by fibers. Permanent malfunctions sometimes occurred because insufficient voltage was available to burn away ingested fibers. In some low-power circuits, in computers, for example, these malfunctions were errors in logic or displays. Most of the equipment found susceptible had low voltage and low

power. Low-voltage, high-power equipment, such as a battery charger and a solenoid, had sufficiently low impedance that the presence of the fibers did not cause malfunctions.

Medium-voltage equipment (15 to 220 volts) usually survived exposures to fibers because the voltage was high enough to burn out the fiber in a short time without damage to the equipment. Such short-duration phenomena may cause malfunctions, but such malfunctions are statistically unlikely because of fiber burnout. Sustained arcs were observed at voltages as low as 50 volts dc provided that sufficient power was available. However, arcs were not sustained in 60-hertz, 110- to 220-volt, single-phase equipment. Although circuit breakers and fuses interrupted the current in this voltage range during testing, no equipment was damaged. This inherent invulnerability of 110-volt devices was demonstrated by tests on appliances, motors, and thermostats.

High-voltage equipment (440 volts, 60 hertz) is used in many industrial applications. Tests of various terminal configurations indicated no sustained arcs for this voltage level on single-phase power drawn from a commercial line. Three-phase systems sometimes sustained fiber-initiated arcs that damaged connectors. This damage was limited by the circuit-protection devices employed (ref. 25). Both single-phase and three-phase circuits with normal terminal spacings sustained arcs if power was drawn from motor-generator sets because of the inductive characteristics of the supply.

Vulnerability of high-voltage distribution-system components (>440 volts) was also investigated (ref. 3). High-voltage power-system insulators (>440 volts) were found to survive exposures in excess of 10^7 fiber-sec/m^3 (for fibers 2 or 4.3 millimeters long) without flashover (ref. 3). Figure 28 is an example of these results. Because the distances across high-voltage insulators are large, multiple fibers must link together to induce flashover. Such linking is unlikely except for extreme depositions. Flashovers occurred at lower exposures ($E \approx 10^5$ fiber-sec/m^3) of longer fibers (9 millimeters), but such long fibers are unlikely to be released in sufficient numbers to constitute a significant hazard.

Because of the specific responsibility of the NASA study to assess the potential need for protection of aircraft, special attention was given to determining the vulnerability of avionics equipment used in scheduled commercial or general aviation aircraft (ref. 52). No equipment had mean exposures to failure $\overline{E}$ less than 10^7 fiber-sec/m^3 even when the test included noise and vibration to simulate the environment of the avionics bays in aircraft. These data, combined with airflow and filtration data pertinent to specific aircraft, were used to evaluate the risk to commercial aircraft safety and the need for protection (refs. 53 to 55). The overall safety and cost risk was insignificant and no aircraft protection was deemed necessary.

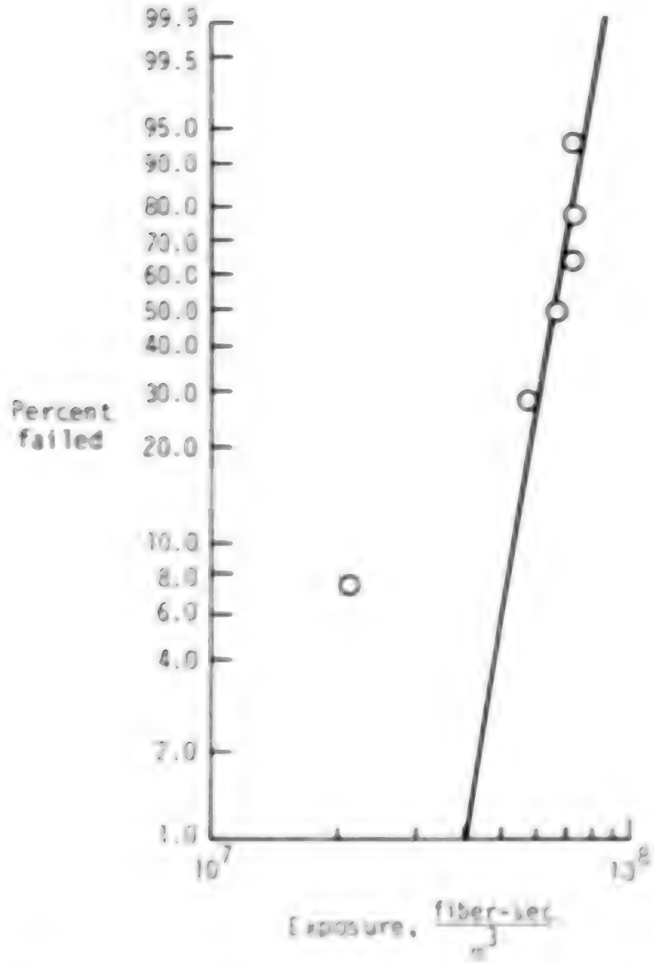


Figure 28.- Exposure to cause flashover for wet 7.5-kV pin insulator. 2 mm fibers.

Results of Fiber Simulator Tests

Detailed studies were made of the specific circuitry and failure modes in a television set, an amplifier, a microprocessor, and a number of smoke detectors (ref. 25). As expected, equipment vulnerability varied with airflow, the number of conductors exposed, and the resistance of the simulated fibers bridging those conductors. The influence of fiber resistance was demonstrated in tests of an amplifier. Fiber simulator probe tests indicated that Thornel 300 (T-300) fibers (resistance 600 kΩ/m) would produce approximately seven times as many malfunctions as would higher resistance (8 MΩ/m) Celion DG-114 fibers (fig. 29). Exposure tests with real fibers (ref. 50) confirmed the relationship, and showed that the mea i exposure to failure $\bar{E}$ for DG-114

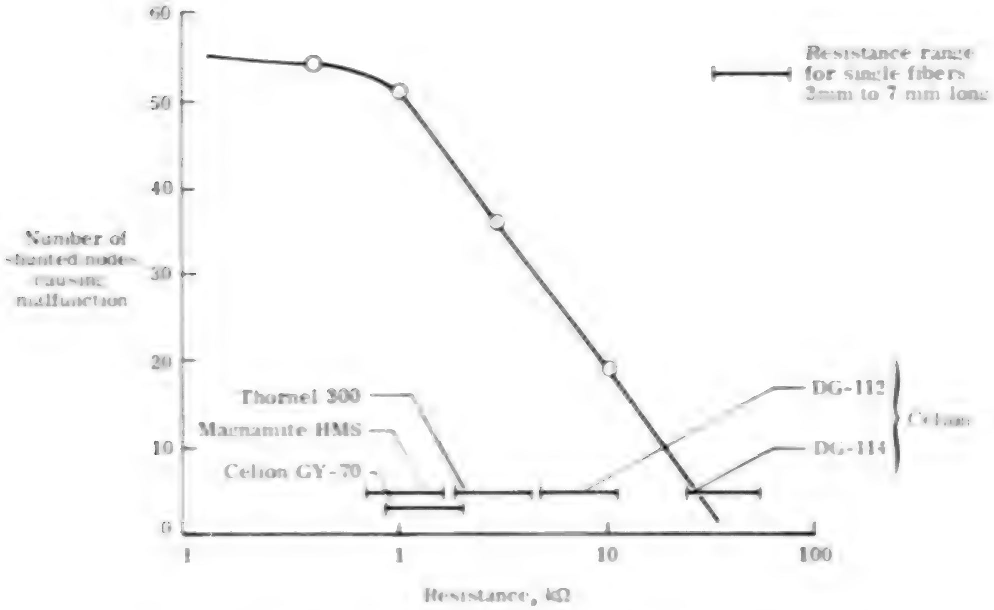


Figure 29.- Amplifier sensitivity to shunt resistance.

fibers was an order of magnitude greater than for T-300 fibers. Figure 30 shows the results of tests in which adjacent and alternate pins of components in a microprocessor were shunted using a fiber simulator. Spacings betwee adjacent pins were 1 to 2 millimeters and between alternate pins were 3 to 5 millimeters. Resistances larger than 1000 ohms did not produce a significant number of failures. From these results, a negligible number of elements in this device would be susceptible to failure from T-300 fibers 2 millimeters long or longer. Under direct exposure in a test chamber, T-300 fibers did not produce a fault even at exposures larger than 10^8 fiber-sec/m^3.

Vulnerability Considerations

Electronic and electrical equipment contains large numbers and various types of discrete and integrated components, circuit board configurations, contact spacings, ventilation schemes, and filtering devices (if present) and operates on voltage sources ranging from a few volts to many thousands of volts. Therefore, only a few general observations regarding vulnerability were possible. Estimates of the vulnerability of equipment was based on these observations.

Ventilation.- The number of fibers which may fall on open electrical equipment is proportional to the concentration, time of exposure, and free-fall rate of the fibers. For this reason, vulnerability is best correlated with exposure E (the integral of concentration over time) for a given system. Case-enclosed electronics generating low convection velocities are relatively invulnerable. When the dissipated power is sufficient to

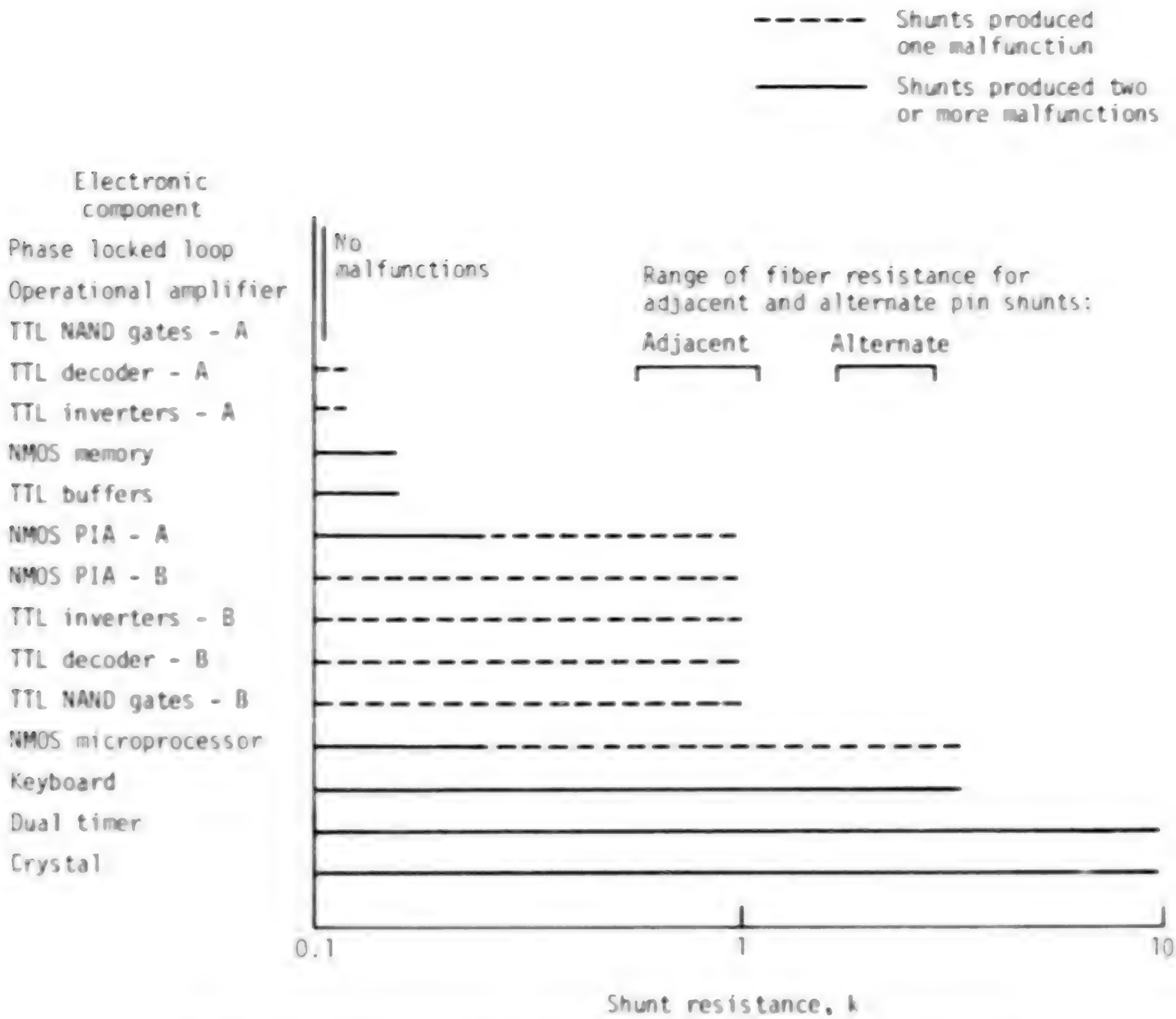


Figure 30.- Microcomputer component sensitivity to resistance of shunt simulating Thornel 300 fibers.

generate convective air velocities larger than the fiber fall velocity, the induced circulation may entrain fibers and, thus, increase deposition density and system susceptibility. The most susceptible systems are those cooled by unfiltered forced air (refs. 25, 50, 52, and 56).

Electronic and electrical circuit and part characteristics.- As shown in figure 31, high vulnerability was exhibited by older equipment using vacuum tubes and other high-impedance components. Modern electronic equipment has highly integrated circuits with few discrete parts and, in general, operates with no ventilation and low power. Thus, it is correspondingly less vulnerable.

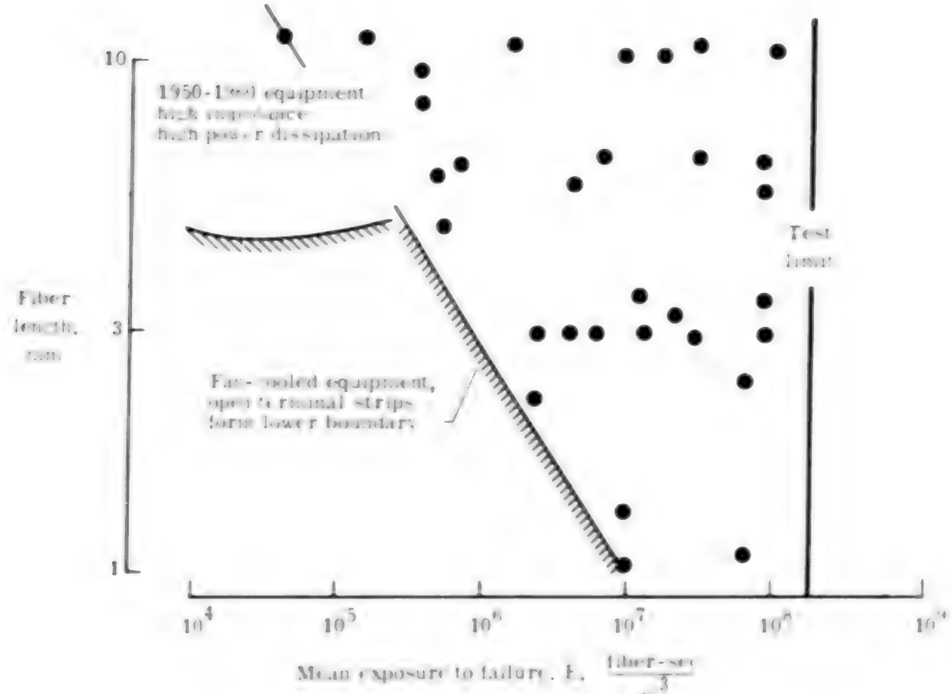


Figure 31.- Mean exposure to failure for vulnerable equipment.

Fiber length effects.- All of the chamber testing was accomplished with single-length fibers. However, the fibers were released in fires at many lengths. In most cases, the following exponential fiber-length distribution function gave a good approximation of the fire-released distribution of lengths:

$$F(\ell) = \left(\frac{1}{\ell_a}\right) \exp(-\ell/\ell_a)$$

where ℓ_a is the average fiber length chosen empirically to fit the equation to the data. From reference 57 the integrated effect of simultaneous exposure of electronics to fibers at a variety of lengths can be estimated by assuming that all fibers released are of length ℓ_a and determining $\bar{E}$, from its experimentally determined variation with fiber length, at a length equal to $\ell_a \sqrt{2}$. This relationship is exact where $\bar{E}$ varies inversely with fiber length squared, and is a good approximation for the full range of experimental variations encountered.

In most of the experiments performed, fibers were collected and counted, and the length averaged for only those lengths exceeding 1 millimeter. For these experimental results, as shown in reference 57, the observed average length should be reduced by 1 millimeter to account for the shorter fibers that were not counted. When this was

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done, the preponderance of data indicated an average length of about 2 millimeters, and the $\bar{\bar{E}}$ for each device obtained with $2\sqrt{2}$ millimeter fiber length was used in the risk analysis.

Although fibers shorter than 1 millimeter were present in significant numbers, they did not contribute appreciably to the electrical hazard identified in this investigation because the equipment tested seldom had conductors spaced closer than 1 millimeter. Individual fibers shorter than 1 millimeter were physically incapable of producing malfunctions. The linking of short fibers, say 0.5 millimeter long, to bridge a 1 millimeter or longer gap is unlikely at exposures below about 10^9 fiber-sec/m^3 (ref. 58). Fibers shorter than 1 millimeter released in realistic fires are expected to provide maximum exposures that are several orders of magnitude lower (ref. 57).

The possible risk for equipment having conductors placed closer than 1 millimeter apart was examined analytically (ref. 57). The mean exposure to failure $\bar{\bar{E}}$ was assumed to be inversely proportional to the fiber length squared because such a power law was found to approximate experimental data for much of the equipment tested in this study. The exponent 2 was chosen in order to be on the safe side of observations; the lowest exponent observed for any unit tested was 2.5. The fiber-length spectrum with the largest numbers of short fibers observed in this investigation was assumed for a hypothetical incident. The contribution to overall probability of failures caused by particular fiber lengths was then calculated. For the particular spectrum used, all fibers shorter than 1 millimeter contributed only 15 percent of all potential failures. Equipment, with such closely spaced conductors, is likely to operate at low power, use coated circuitry, and be housed in well-sealed enclosures. All these factors render such equipment nearly immune to carbon fiber electrical problems.

These observations justified the emphasis of this study on electrical risk from fibers longer than 1 millimeter.

Attenuation of Electromagnetic Signals

A theoretical study (ref. 25) was performed to quantify the degradation of instrument landing aids due to attenuation of radio-frequency signals by deposits or clouds of carbon fibers released from a fire involving carbon fiber composite material. The two situations considered were (1) carbon fiber deposits on antenna radomes and (2) transmission paths intersecting fire plumes with significant concentrations of carbon fibers. The current Instrument Landing Systems (ILS) operating at 75, 110, and 330 megahertz, and the future Microwave Landing Systems (MLS) operating at 1 and 5 gigahertz were considered. Maximum fiber concentrations in clouds of 10^3 fibers/m^3, maximum fiber depositions on radomes of 10^4 fibers/m^2, and maximum fiber length-to-diameter ratios

of 1000 were assumed. No bias errors were predicted and the predicted attenuations were negligible (<1 decibel) except for MLS, 5-gigahertz transmission through a fiber cloud (fire plume) which is oriented directly along the path to an approaching aircraft. In this case, the attenuation may be enough to reduce the system operating range by approximately 30 percent. This means that the guidance system would provide the correct path to the ground even when the aircraft was flying the approach through a continuous cloud of carbon fibers, but that guidance signals might not be acquired beyond 70 percent of normal range.

Application of Results

Experiments on vulnerability of electrical and electronic equipment were generally performed with five or more exposures to failure to determine the mean exposure to failure $\bar{E}$. This was accomplished at each of a number of fiber lengths. In realistic situations, the actual exposure E is likely to be one or more orders of magnitude smaller than $\bar{E}$. To apply the observations to these practical exposures, analysis (refs. 58 and 59) shows that the probability of failure P_f due to exposure to single fibers is

$$P_f = 1 - e^{-E/\bar{E}}$$

When $E/\bar{E} < 0.1$, this probability is closely approximated by $P_f = E/\bar{E}$. All risk assessments made in this study employed the exponential failure law or this linear approximation. The resulting failure probabilities at low exposures are inherently on the safe side (perhaps by orders of magnitude), because the only other modes of failure require multiple fibers to link together and the probabilities of such occurrences are very much smaller.

FACILITY SURVEYS

Objectives of Surveys

Facilities were surveyed to provide the data required to make economic predictions of carbon-fiber-induced incidents throughout the nation. The 63 facilities listed in table III were visited by technical teams. The list includes representative public, utility, commercial, and industrial facilities.

TABLE III.- SUMMARY OF FACILITIES SURVEYED

Type of facility	No.	Type of facility	No.
Public		Commercial	
Hospitals	7	Department stores	2
Air traffic controls	6	Financial institutions	2
Airports-airlines	3	Radio and television stations	6
Police headquarters	2	Analytical laboratories	1
Fire dispatch	2	Manufacturing	
Post offices	1	Meat packing	1
Traffic control	1	Textile mill	1
Utilities		Garments	1
Telephone exchanges	3	Pulp and paper	1
Power generation and distribution	3	Publishing	2
		Textile fibers	1
Refuse incinerators	2	Toiletries	1
AMTRAK Railway System	1	Steel mills	2
		Wire, cable	1
		Electrical equipment	6
		Automotive fabrication and assembly	4

The following data were gathered for each facility surveyed:

- Listings of equipment by types (computers, controls, instruments, etc.) and quantities
- Description of the way equipment was employed in the operation of the facility (part of an automated line, one of many identical units, etc.)
- Description of the ventilation systems and existing protective elements (separate rooms, shielding, sealed cases, coated circuit boards, etc.)

The listings of equipment guided the selections of items for exposure testing which, in turn, provided a basis for selection of $\overline{E}$ (mean exposure to failure) used in the prediction of failures. The mode-of-use descriptions supported the definition of the economic impact from an electrical failure in such terms as repairs, lost worker time, lost production, and spoiled product. The data from the ventilation system and protective measures supported the calculations for transfer functions into buildings and equipment. The specific descriptions of air-conditioner filters guided the selection of candidate elements for exposure testing.

The surveys found that many plants operate electrical equipment in environments such as dust, moisture, corrosive liquids, or combustible fluids. Protection of equipment from such environments also effectively shields it from airborne carbon fibers. The surveys identified that portion of industry which might be vulnerable and estimated the degree of that vulnerability. Because failures of electrical equipment in hospital operating rooms and air traffic controls could threaten human lives and failures in power generating stations and telephone exchanges could adversely affect entire communities, these activities were studied in detail.

The following paragraphs present the results from the surveys.

Public Facilities

Public facilities include those areas where electronic or electrical equipment performs life-critical functions, such as in hospital operating rooms, in air traffic control centers, or in communication systems for ambulance, police, and fire units. Hospital operating rooms, intensive-care units, and cardiac-care units are equipped with air-conditioning and filtration that removes airborne contaminants; such filters also remove carbon fibers from the air. Air traffic control towers are generally equipped with special air-conditioning systems to cool the many electronic items employed which generate considerable heat. Remotely mounted radars and transmitters are protected from weather and are shielded from radio-frequency interference. This combination of protection would also prevent carbon fibers from entering the systems (ref. 2). Airport terminal buildings have special ventilation systems with activated carbon filters to remove kerosene fumes and other contaminants found at airports; such filters also trap carbon fibers. Two-way communication with emergency vehicles, such as ambulance, police, and fire units, frequently involves more than one dispatcher working with more than one vehicle. An interruption at one dispatcher location would not disable the entire communication system. Within a vehicle, the road environments of heat, vibration, moisture, and corrosion dictate the use of either sealed or otherwise well-protected electronic units (ref. 3). The surveys of these areas could not identify any threats to human life or safety.

Other public facilities contained equipment which could be subject to failure caused by airborne carbon fibers. These installations had identifiable responses that would limit the impact of a failure incident. For example, in a post office, the failure of an electronic sorter results in heavier loads on alternate units or forces a return to hand sorting while the unit is repaired. For equipment in such public facilities, the economic impact of carbon-fiber-induced failures would usually be the cost of troubleshooting and repair.

Utilities

Electrical failures in telephone exchanges or electrical power stations could have an important impact upon a community. The surveys revealed that modern electronic exchanges are housed in sealed, air-conditioned buildings offering little or no entrance for airborne carbon fibers and, thus, are invulnerable to damage. Older exchanges are more accessible; carbon fibers could enter and cause some elements to fail. However, much of this equipment operates in the voltage range considered immune to fibers. Telephone exchanges contain large numbers of the same basic elements of equipment operating with continuous maintenance. In general, failures and malfunctions are located and corrected within 15 minutes.

In power generation and distribution, only the newer generating stations utilize electrical circuitry which operates in the voltage range considered sensitive to carbon fibers, and all the critical items are located within the control rooms. Such control rooms use filtration and air-conditioning systems to meet heat and cleanliness requirements. Tests on filter elements have shown that they prevent the passage of carbon fibers (i.e., transfer functions less than 10^{-5} (refs. 25 and 42)). Municipal incinerators must contend with explosive dust; therefore, their electrical installations are sealed and are essentially invulnerable to carbon fibers.

For utilities, airborne carbon fibers can be expected to cause some failures in older telephone exchanges and within the general purpose type items which support operations. The principal economic impact would be the costs associated with troubleshooting and repair.

Commercial Facilities

Some commercial institutions (such as banks and insurance companies) depend critically upon data stored in central computers. A failure which disturbed such records would constitute a major economic loss. To carry away the heat generated by the equipment and to provide the isolation needed for efficient operation, the central units of such computers are housed in special, independently ventilated and air-conditioned rooms. These measures appear sufficient to protect critical records against errors or other damage by carbon fibers. The other equipment in commercial installations is not protected to the same degree. Carbon fibers which enter commercial buildings through doors or ventilation systems can find their way into items such as cash registers, calculators, and point-of-sale terminals. These items have been tested for vulnerability (ref. 50).

Radio and television stations utilize a substantial amount of electronic equipment mounted in relatively open cabinets. Airborne fibers entering a control room or a

transmitter site can cause electrical failures of individual units. However, most studios install their equipment in a number of small rooms isolated from each other; thus, the total shutdown of a station would require a number of nearly simultaneous failures.

Generally, exposure to airborne carbon fibers could result in a number of failures within items of working equipment in commercial facilities. In some cases, spare units may be available. The economic impact becomes the cost of troubleshooting and repair plus any costs associated with substituting the spare and with the disruption of the service provided by that piece of equipment.

Manufacturing Plants

The selection of a representative cross section of manufacturing facilities was guided by statistics from the Bureau of the Census and utilized their Standard Industrial Classification (SIC). The 21 manufacturing plants surveyed are typical of facilities which produce 85 percent of the total value of shipments attributed to the U.S. domestic industry. All depended upon electrical or electronic equipment. In four classes of operations, electrical failures could have a major economic impact. In a continuous-process type of production (e.g., papermaking and textile fiber spinning), failure of a control system could spoil some of the product and then require overtime premiums to regain the production lost. In an assembly line, a failure could idle a work force and impose a loss of production. In an automated production line, a failure could idle a work force, spoil some of the product in the line, and incur substantial costs during the recovery of production. In the manufacture of electronic or electrical equipment, carbon fibers could damage production equipment and perhaps leave latent failures within the delivered product.

Protective measures now employed to guard against failures attributable to particular environmental concerns also minimize or prevent failures from airborne carbon fibers. For example, many control system elements for the continuous-process industries operate in corrosive environments of pulp mills and chemical plants. The protection (coated circuit boards, sealed cases, etc.) used on controls operating in corrosive fumes also protects against airborne carbon fibers (ref. 25). Critical assembly lines are continuously monitored for breakdown or bottlenecks; a problem receives immediate attention to minimize the interruption of services. Wherever an assembly line must utilize failure-prone equipment, spare or backup units are available. Numerically controlled machine tools are major users of electronics in automated production lines. Here, the environment of cutting lubricants and machining debris dictate the use of sealed or well-filtered enclosures. The manufacturers of electronic equipment employ "clean rooms" to provide cleanliness during the critical steps of populating circuit boards, soldering leads, and final assembly. The air-conditioning and filters used in these rooms also provide protection from airborne carbon fibers. These patterns of protection extend

into other industries. For instance, many rooms of food processing plants are routinely washed down to maintain high standards of sanitation and cleanliness. Electronic weighing devices are protected against such washings and, consequently, against carbon fibers. Mass production industries, machine shops, and printing plants usually must control temperature, dust, or humidity to achieve the environmental conditions conducive to good quality in their products.

The installation of industrial electrical circuitry is governed by wiring codes formulated by the National Electric Manufacturers Association (NEMA). They define twelve classes of wiring enclosures for industrial applications. Of these, only three permit openings which admit as many as 1 percent of carbon fibers present in the surrounding area (ref. 25). Thus, industrial electrical equipment receives substantial protection against carbon fibers through use of standard electrical enclosures.

Facility Classification

The foregoing data and observations were used to characterize the features of industrial installations throughout the country. The characterizations were made for each of a large number of generic categories listed in the Standard Industrial Classification (SIC), prepared by the Bureau of Census. Each category was described by building type, ventilation scheme, unique internal environment, vulnerability of equipment, and qualitative impact of a failure. These data become the basis for the economic evaluations described in the next section.

RISK ASSESSMENT

Computations

The risk assessment involved computation of the possible economic impact of damage to electrical and electronic equipment caused by released carbon fibers. As discussed in previous sections, the probability of shock hazards was extremely remote and no health hazards from carbon fibers had been identified. Therefore, no further consideration was given in the risk assessment to the possibility of human injury or death. Further, since analyses and tests have shown that only single fibers longer than 1 millimeter contribute significantly to electrical and electronic failures, the risk computations were limited to the calculation of the economic consequences of electrical failures caused by release of single carbon fibers longer than 1 millimeter.

Two contractors – ORI, Inc., and Arthur D. Little, Inc. (ADL) – were chosen to assemble and supplement data developed under NASA auspices as described in the preceding sections of this report and to independently develop methods and make risk computations. Both contractors analyzed the risks associated with the use of carbon fibers in

commercial transport aircraft (refs. 60 and 61) and assessed the extent of carbon-fiber-induced outages in power distribution systems (refs. 61 and 62). ADL also analyzed the risk associated with the use of carbon fibers in general aviation aircraft (ref. 63).

Carbon fiber risk from commercial transport aircraft accidents.- In computing the risk associated with the use of carbon fibers in commercial aircraft, many thousands of aircraft accidents were simulated. Each accident was characterized by numerous variables. The contractors made extensive use of statistical techniques in the simulations and associated analyses. They used similar computational methods; however, their choice and treatment of the variables differed as did their synthesis of the results of the individual accident simulations into national risk profiles. Tables IV and V outline the computational steps and the variables used by the contractors in performing the carbon fiber risk computations for commercial aircraft.

Individual accidents were simulated by random selections of a number of variables associated with the accident location, the operational mode, the type of aircraft, the extent to which carbon fibers were involved, and whether or not explosion occurred. The values of the variables and their distribution were based on detailed analysis of National Transportation Safety Board records and records of jet aircraft accidents in which fires were involved (refs. 7 and 8). The projected mix of aircraft in the fleet for the target year of 1993, the extent of carbon fiber usage in the fleet, the fraction affected by fire, and the fraction of available carbon fiber released as single fibers over 1 millimeter long were established in accordance with data presented in the "Fiber Source" section of this report. The behavior of the fire plume that carries the released fibers aloft and the downwind transport and diffusion processes were modeled (refs. 64 and 65) using established methods discussed in the "Fiber Transport" section of this report. The necessary meteorological inputs for these calculations were drawn at random from local weather statistics for each of the airports for which the calculations were made.

The transport and diffusion calculations provided the fiber exposures or dosages up to 80 kilometers downwind of the simulated accident. The downwind areas were subdivided into sectors. The distributions of businesses, industries, public facilities, and private residences within these sectors were then determined from county-based economic and census data. Categories were established which grouped similar types of facilities. Building types and equipment complements were assigned according to data gathered during the facility surveys discussed in an earlier section of this report. Building types were characterized by ventilation parameters obtained from standard engineering sources and modified by particular experimental data appropriate to the carbon fibers. These parameters were used to calculate the transfer function, or the fraction of the fibers outside each building that would enter. The risk assessment model thus determined the exposure or dosage to which vulnerable equipment was subjected. Mean

TABLE IV. - ADL RISK COMPUTATION

Parameter	How established
Airport	Select one of 26 airports
Size of aircraft	Random selection of small, medium, large from fleet mix for airport
Composite mass per aircraft	Random selection from a distribution for each aircraft size
Percent of composite involved	Estimate from accident statistics and where carbon fiber is used in structure
Phase of operation	Random selection of take-off, landing, or other from accident statistics
Likelihood of explosion	Random selection of 0 or 1 from statistics for each phase. Mean = 5.4 percent
Percent of fiber released[a]	1 percent for 94.6 percent fire-only accidents or 3.5 percent for 5.4 percent fire-plus-explosion accidents
Radial distance from airport center	Random selection of 0, 1, 10 km from accident statistics
Azimuth from airport center	Random selection of 0° to 360° from runway angle and usage statistics
Wind velocity	Random selection from local weather statistics
Wind direction	Random selection from local weather statistics
Temperature	Random selection from local weather statistics
Pasquill stability class	Random selection from 1 to 6 from weather statistics
Quantity of fuel carried	Fixed by type of aircraft, phase of operation
Quantity of fuel burned	Random selection, 0 to 100 percent, from accident statistics
Duration of fire	Random selection, 2 to 35 min, from accident statistics and quantity of fuel burned
Plume width at equilibrium altitude	Calculate from fire dynamics and stability class
Virtual point source of fibers:	
Fire only	Calculate from plume width at equilibrium altitude
Explosion	Ground level
E-distributions	From plume, transport equations, wind direction calculated for 8 octants, 5 radial bands, and 50 points within each such sector downwind
Facility demography	From county census data for 15 SIC categories for same radial-octal points as above
Transfer function	By SIC categories, season, filters, seals, etc
Vulnerability $\bar{E}$	For 153 equipment types in 15 facility categories
Cost of failures, repair	5 severities, for each of 15 SIC categories, \$80 to \$2500
Cost of failures, disruption	3 severities, value depends on size of facility
Cost per accident	Calculate from foregoing
Costs for many accidents at airport	Calculate from foregoing
Single-accident cost profile for airport	Calculate from foregoing
Costs for 25 other airports	Calculate from foregoing
Single-accident cost profile for nation	Calculate from airport profiles weighted by airport share of national operations considering weather factors
National annual risk profile	Calculate from foregoing via random selection of accidents per year from Poisson distribution with Mean = 2.7

[a] 3.5 percent was used, not 2.5 percent as reported in reference [illegible].

TABLE V.- ORI RISK COMPUTATION

Parameter	How established
Size of aircraft	Small, medium, or large per fleet mix
Airport	1 of 9 airports per usage by aircraft sizes
Accidents per year with fire and carbon fiber	0 or 1 per airport from Poisson distribution with Mean = 2.6 per year Joint random selection
Amount of carbon fiber involved	Random selection, 0 to 469 kg, depends on 19 aircraft types, 2 operational phases, 2 severities of damage
Amount of carbon fiber released	1 percent for fire only in 97 percent of accidents, 3.5 percent for explosions in 3 percent of accidents
Plume height	Calculate from fuel carried for each aircraft size, 3 operational phases, 2 severities, limit by inversion altitude
Wind speed	
Wind direction	Joint random selection from local weather statistics
Pasquill stability	
Exposure E	Calculate for 5 points in each county up to 80 km away
Transfer functions	Mean values for 7 categories of buildings
Vulnerability $\bar{E}$	Assign by 15 equipment types in 20 SIC categories per county
Complete failures of industries	Random selection from $E/\bar{E}$ per SIC categories (primary power)
Partial failures of industries	Random selection from $E/\bar{E}$ per SIC categories (internal)
Cost per accident	Calculate from expected values of repair, lost time, and product: For industry, by counties and SIC categories, number of employees, payroll, and share of GDP For households, by county census, \$50 per TV, \$100 per hi-fi failed For avionics, by aircraft at gate or maintenance docks, considering day-night, 15 vulnerable equipment categories, ventilation factors for each
Costs for 2500 accidents	
Costs for 8 other airports	
National risk profile	Random selection from airport cost distributions, number of selections for yearly set from Poisson distribution with Mean = 2.6 accidents per year

exposure to failure $\bar{E}$ for equipment and equipment combinations were established based on data discussed in the "Vulnerability of Equipment and Shock Hazard" section of this report. From the calculated interior exposures, either a likely number of failures (ORI) or the probability of failure (ADL) was computed for specific classes of vulnerable equipment in each type of business, industry, and public facility. Impact on households was assessed by computing the expected cost and probability of failure. The repair cost for damaged business, industrial, and public facility equipment was estimated for generic classes of equipment. Impact on facility operations was assessed as either the loss of one day's share of gross domestic product (ORI) or an expected-value loss based on

economic analysis of typical facilities visited during facility surveys (ADL). The vulnerability of avionics equipment aboard aircraft parked at an airport was included in the above computation. The number of aircraft in a potentially vulnerable state at each of the airports was determined from data provided by the aircraft manufacturers (refs. 53, 54, and 55).

From the foregoing costs of failures in industries, businesses, public facilities, households, and parked aircraft, the models generated an estimate of the total economic impact of one accident. This process was repeated until a sufficient number of accidents had been simulated to establish a stable distribution of individual accident costs for an airport.

ORI selected nine major airports as representative of all U.S. airports handling commercial jet operations. They distributed the number of accidents occurring in a year (determined from a Poisson distribution) to these airports in proportion to their prorated share of U.S. operations. Costs were summed for individual years and the process was repeated until a stable distribution of yearly costs was obtained. The ORI national annual risk profile was developed from this distribution.

ADL selected 26 airports to represent all U.S. airports having commercial jet operations. From the individual accident distributions for the separate airports, they developed a national distribution for costs of one accident. They then drew from this distribution to obtain the costs of yearly sets of accidents, from which a national annual distribution and a risk profile were developed.

Carbon fiber risk from general aviation aircraft accidents.- The use of the foregoing procedures to analyze risk from general aviation accidents would have required a prohibitive effort because these accidents occur with much greater frequency and at much more widely scattered points. On the other hand, much smaller quantities of carbon fiber are likely to be released and, therefore, a much smaller risk is involved in a given accident.

Accordingly, ADL developed a simplified analytic approach (ref. 63) that employed expected values for many of the input data as follows:

- The size of the 1993 fleet of general aviation aircraft and the number that would carry carbon fiber composites were estimated. For three classes of aircraft, the expected mass of such composites per aircraft was computed: for single-engine airplanes, 7.0 kilograms; for twin-engine and jet-engine airplanes, 20.5 kilograms; and for rotary-wing and unpowered aircraft, 50.5 kilograms.

- The mass of fiber that was expected to be released from each of these three categories of aircraft was taken to be 2.9 percent of the fiber carried in fire accidents that led to total destruction and 0.76 percent in accidents with substantial damage of the airframe.
- The fibers released were assumed to be uniformly distributed over the county in which any accident occurred.
- Of the 354 general aviation accidents expected per year, 88 were expected to involve carbon fibers and fire, and these were allocated to 3000 counties in the United States according to each county's share of the total operations.
- The potentially vulnerable industrial, business, and household equipment was cataloged into 81 categories for each of the 3000 counties. Appropriate filter factors and vulnerabilities were assigned to the 81 categories.

The quantities thus defined were statistically combined and appropriate weighting factors applied to establish a mean number of equipment failures per accident. Failures were expected to occur in proportion to $E/\overline{E}$, as discussed in the section on vulnerability. Because very small masses of fibers were expected to be released in any accident, the mean number of failures per accident was only 0.022. About 98 percent of all accidents were not expected to cause any failures.

A cost was assigned to each failure depending on the cost of repair and the impact on industrial operations, if applicable. These costs were transformed to mean costs per failure by taking a weighted average for the 81 equipment categories and the likelihood of occurrence for each failure. Because the overwhelming majority of failures are expected to occur in readily repaired industrial and household equipment, the expected cost per failure was small, \$131.

The product of 0.022 (failures per accident) and \$131 (cost per failure) yielded a mean cost of only \$2.88 per accident. The mean national risk was taken to be 88 (the expected number of accidents) times \$2.88, or \$253 per year. Because the number of accidents per year and the number of failures per accident are appropriately assumed to be random variables with Poisson distributions, their means also determine their variance. From this, the standard deviation of annual national risk was computed to be \$1067.

Although this simplified method provides estimates of the expected loss and its variability, it does not adequately define the distribution of costs, particularly for the rarely occurring, but possible, high-cost incidents. However, upper bounds were computed for the probability of occurrence of the high-cost accidents.

To provide a comparison of predictions by this method with predictions made in other ways, ADL used the same method to analyze the transport aircraft risk described earlier.

Analysis Results

The national annual carbon fiber risk profiles developed by ORI and ADL from the commercial aircraft accident simulations are shown in figure 32. Mean annual damage

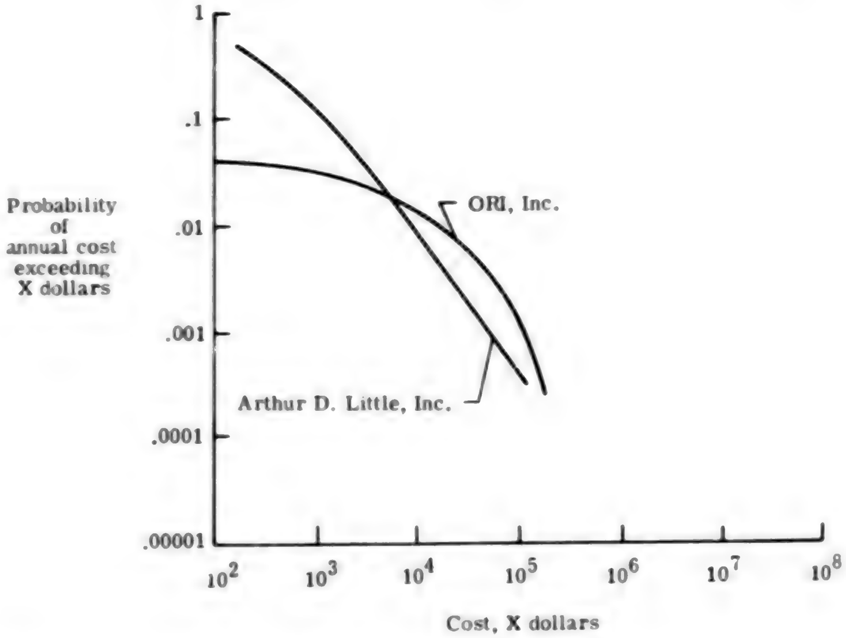

Figure 32.- 1993 national risk profile for carbon fiber released from commercial aircraft accidents. 1976 dollars; 1993 carbon fiber usage assumed.

estimates of approximately $470 were calculated by both ORI and ADL; however, the ORI estimate had a somewhat higher standard deviation. The costliest accidents were $178 000 in the ORI simulation and $74 000 in the ADL simulation. Both studies found that damage was sustained principally by business and industry. Household damage contributed about a third of the costs in a typical ADL accident simulation and averaged less than 3 percent in the ORI simulations. Avionics costs were extremely small.

The ADL simplified analysis of commercial aircraft crash fires predicted a mean annual damage of $1220. This analysis also indicated a slightly higher probability of high-cost accidents.

The probability of failure of avionics in other aircraft in the vicinity of an accident was analyzed separately by the aircraft manufacturers (refs. 53, 54, and 55). The expected number of avionic equipment failures due to carbon composite crash fires was found to be on the order of 0.0003 percent of the current normal operational failure rate. No situations were identified in which the safety of the aircraft was affected.

The sensitivity of the risk from commercial aircraft accidents to variations in input parameters was analyzed. Table VI shows the effect of five changes on mean damage and standard deviations. The effects on the risk profile, in most instances, are roughly equal to the change in input parameters.

TABLE VI.- COST SENSITIVITY

Change to input	Mean damage changed by factor of -	Standard deviation changed by factor of -
Released carbon fibers doubled	2	2
Accident rate doubled	2	1.7
All aircraft have 10 954 kg of carbon fiber (7 times average)	7	4.5
Explosions with all fires (3.5 times fire-only fiber release)	3	2
Weather always stable (Class E)	1.5	1.2

Both ADL and ORI calculated confidence bounds for their risk profiles as they are affected by the number of simulations. Both showed that, with 95 percent confidence, the risk profiles reflect costs to within a factor of two of what an infinite number of simulations would provide. A judgment on the overall confidence limits is difficult to establish because whenever doubt existed regarding a parameter, a conservative value was used in the analysis. Therefore, the profiles should represent upper bounds on the 1993 risk. Reference 66 contains an independent investigation of various statistical aspects of carbon fiber risk assessment modeling.

The ADL analysis of general aviation crash fires in 1993 indicates that the mean damage from carbon fiber was $253 annually with only one chance in 10 000 of exceeding $110 000 in damage (ref. 63).

Both ORI and ADL made separate analyses of possible power outages resulting from carbon fiber releases. Their work was based on vulnerability of high-voltage electrical

insulation developed by the Department of Energy and reported in reference 3. The ADL analysis (ref. 62) was based on the area coverage equation for exposure (ref. 35) to estimate the maximum number of insulators which could fail during any release. This resulted in an upper bound estimate that 0.7 customers per year would be affected by a power outage. The ORI analysis (ref. 61) assumed that all U.S. jet transport accidents occurred at Los Angeles, that all were worst-case accidents, and that the wind always blew the cloud toward the most critical area. This calculation showed that 23 customers per year would be affected by a power outage, or one carbon-fiber-induced outage would occur for every 200 000 to 1 000 000 that occur for other reasons.

Some of the airborne debris from composite fires was in single-lamina strips. These strips can fall across power line parts and cause momentary arcs. An analysis of the expected distribution of such strips (ref. 2) showed that 1-meter-long strips could have deposition densities as high as 0.5 strip/m^2 within the first few hundred meters downwind of a crash. The probability that such a strip would land on a power line pair spaced 0.6 meter apart was calculated to be 1 in 1000 in an accident involving 10 000 kilograms of composites (ref. 58). Thus, the risk to the power distribution network from carbon composite lamina strips is insignificant.

Discussion of Results

The carbon composites used in all of the tests are examples of the type that are currently or contemplated to be in use in civil and military aircraft. Improvements could result in products that, when burned, release either a larger or smaller amount of carbon fiber or result in a carbon fiber that is more or less damaging to electrical or electronic equipment. However, because several years of evaluation are required to certify a new material for aircraft applications, any new material is unlikely to receive more than token acceptance by 1993, the year chosen as the focus for this study.

Basing the vulnerability of equipment on the current practice in electrical and electronic equipment ignores a technology trend that will provide a very substantial reduction in equipment vulnerability. Several factors are expected to affect vulnerability: the increased use of coated circuit boards and integrated circuits, the reduced power requirements of solid-state electronics, and the recent aircraft practice of totally enclosing or filtering and air-conditioning electronics. All reduce the potential damage that carbon fibers can cause. The stimulus for each of these practices is the need for highly reliable low-cost electronic systems. One factor that may not have been fully evaluated was the potential growth, in the next 15 years, in the numbers and types of potentially vulnerable equipment. However, this factor is expected to be outweighed by the trend to improve equipment.

The analysis assumed that carbon fiber debris at the accident site is cleaned up. (This is the current standard practice for military aircraft crashes.) The test results show that most of the fire-damaged carbon composite remains on the ground at the accident site as charred and partially oxidized carbon fiber held together by products of combustion. The amount of debris remaining was found to be many times that lofted into the air by the fire. This debris represents a potential delayed source of airborne carbon fiber and therefore should be removed. Care should be taken to prevent agitation of this debris before and during the cleanup. Fiber "hold-down" chemicals, such as polyacrylic acid (PAA), are being developed to prevent the spread of free fibers from crash sites. When sprayed on carbon composite debris, the chemical coats the carbon fibers and prevents them from being released upon handling of the fire debris. The additional cost of the cleanup and the preventive treatment of the debris (minor by comparison to the total cost of an accident) was not taken into account in the estimate of the public risk.

The predicted damage from release of carbon fibers during burning of composite structures should be judged acceptable or unacceptable by comparison with other risks or benefits associated with the ultimate use. Two measures may reasonably be chosen for comparison: the benefit associated with carbon fiber application and the cost of the accidents.

The benefit obtained in the application of carbon composites to commercial aircraft is well recognized. The manufacturer of one aircraft under construction estimates that the use of only 400 kilograms of carbon fiber in the structure results in a reduction of 400 kilograms of fuel used per day. The fuel savings over the life of the aircraft is very significant.

The total costs of 155 air transport accidents occurring between 1966 and 1975 have been studied by the Federal Aviation Administration (ref. 67) and by one of the contractors performing the risk computations (ref. 61). Accident cost (in 1974 dollars) ranged from less than 1 million dollars to nearly 50 million dollars per aircraft (non-fire accidents were included). The mean cost of those accidents, where the aircraft sustained at least substantial damage, ranged from 5 million dollars for small jet aircraft to in excess of 10 million dollars for large jet aircraft. Considering the number of aircraft crashes, the potential damage from released carbon fiber must be compared with annual aircraft crash costs of nearly 100 million dollars. Relative to such costs even the $178 000, worst-case incident simulated (having a probability of occurrence of once in 34 000 years) is a low-cost event.

CONCLUSIONS

A comprehensive assessment of the possible damage to electrical and electronic equipment caused by accidental release of carbon fibers from burning civil aircraft with carbon composite parts has been completed. The study concluded that the amount of fiber likely to be released is much lower than initially predicted. Carbon fiber released from an aircraft crash fire was found (from atmospheric dissemination models) to disperse over a much larger area than originally estimated, with correspondingly lower fiber concentrations. Long-term redissemination of fiber was shown to be insignificant if reasonable care is exercised in accident cleanup. The vulnerability of electrical equipment to structural fibers in current use was low. Consumer appliances, industrial electronics, and avionics were essentially invulnerable to carbon fibers. Shock hazards (and thus potential injury or death) were found to be extremely unlikely.

The overall costs were shown to be extremely low in 1993, the year chosen as a focus of the study. The expected annual cost was shown to be less than \$1000 with only one chance in 2000 of exceeding \$150 000 loss annually. For comparison, the costs of air transport aircraft accidents occurring between 1966 and 1975 range from less than 1 million dollars to nearly 50 million dollars per accident (non-fire accidents are included). The mean cost of those accidents, where the aircraft sustained at least substantial damage, was about 6 million dollars. Thus, even the worst-case carbon fiber incident simulated is relatively low cost.

The following conclusions are drawn from these results:

- The risk of electrical or electronic failures due to carbon fibers should not prevent exploitation of carbon composites in aircraft.
- Additional protection of aircraft avionics to guard against carbon fibers is unnecessary.
- A program to develop alternate materials specifically to overcome the potential electrical hazard is not justified.

APPENDIX C – NASA STUDIES ON MODIFICATION OF CARBON/GRAPHITE FIBERS AND ALTERNATIVE MATERIALS

In addition to the task of assessing the risk associated with the use of graphite fiber composites in commercial aircraft, NASA was charged to explore the feasibility of modifying resin matrix composites to reduce the potential of electrical shorting from fire released fiber. This effort was conducted at NASA laboratories at Langley, Lewis, Ames, Marshall, and JPL and by numerous contractors. The effort included modifications to or coatings for graphite fibers, alternative fibers, modifications to matrix materials, and hybrid composites. The objectives included reduction of the conductivity of the graphite fibers, char formation to reduce fiber release, glass formation to prevent fiber release, catalysis to assure fiber consumption in a fire, and replacement of the graphite fibers with nonconductive fibers of similar mechanical potential.

The NASA Langley Research Center (LaRC) program was directed toward carbon fiber modification and coatings, matrix modification, and hybrid composites.

Large increases in the electrical resistance of commercial fibers were obtained by forming a graphite oxide coating. Five commercial fibers were used: type P, GY-70, T300, HMS, and HTS. The graphite oxides were obtained by treating the fiber with strong oxidizing acids. The resistance of three of these fibers (T300, GY-70, and type P) after treatment were as high or higher than the resistance needed to minimize a short circuit, i.e., 10^5 ohm/cm. However, the tensile properties of these fibers were downgraded by 25 to 50 percent. This degradation may be due to handling, as well as the oxidation process. Although the graphite-oxides are fairly stable at room temperature, the stability at high temperature was not determined. Although this process did result in fibers with high electrical resistance, the fibers were not suitable for structural applications.

Fiber coating research was conducted to explore processes to get thin (0.1 μm), uniform inorganic coatings on individual fibers. The resistance of HMS fibers coated with SiC/SiO_2 by chemical vapor deposition (CVD) methods has been measured at 10^5 ohm/cm or higher. The filament strength was not degraded and increases in the composite shear and flexure strengths were observed. The electrical resistance of the coated filaments was not significantly changed after the epoxy resin composite containing these fibers was subjected to a simulated aircraft fire. Fibers were also coated with Si_3N_4 and BN by CVD methods. Exploratory studies showed that these coated fibers have resistance of 10^9 ohm/cm but with significant degradation of the fiber tensile strength. With process optimization, it appears that coatings of this type might be successfully developed.

In on-going programs, the Navy and LaRC were jointly supporting a program to develop a boron nitride (BN) fiber. Data on the BN fiber show that the tensile modulus is greater than that of typical graphite fibers. However, the tensile strength of the BN fiber is less than that of the carbon fibers. Research to date indicates that the strength might be increased to that of the T300 fiber without a significant change in the modulus.

Preliminary test data have shown that hybrids can significantly reduce the quantity of fibers released from the impact of a burned composite. Both shell-core (formed by replacing top and bottom Gr Ep plies) and interspersed hybrids (formed by distributing particles between Gr Ep plies) were fabricated and tested in a simulated aircraft fire as well as tested to determine mechanical properties. Data from preliminary screening tests on the shell type hybrid show that hybrids containing glass shells reduce fiber release better than the shell-core hybrids tested. Similar data on the interspersed hybrid show that low-temperature melting glass fillers show promise in causing clumping of graphite fibers. Both analytical and experimental data show that the mechanical properties of the shell-core hybrids are sensitive to the number of nongraphite plies. Therefore, the hybrids must be carefully designed to maintain the desired mechanical strengths and to reduce fiber release. Tests were conducted to determine the importance of ply orientation, test temperature, and stream oxygen content on fiber release.

Organic sizings and fiber-surface treatments to increase char formation and fiber clumping were also investigated. Test data indicated that neither the sizing nor the surface treatments significantly reduced fiber release.

The NASA-Lewis Material Modification Program included studies in synthesis of new and improved matrix resins, development of ultra-high modulus organic fiber reinforced composites, and hybridized composites.

The objective of the synthesis studies was to develop matrix resins which would provide a high char yield when subjected to burning. It was postulated that the higher char yield would be an effective means of containing the carbon fibers in a burned composite. Research resulted in the development of a novel class of curing agents for epoxy resins which significantly increased the char yield. Composites prepared with the modified epoxy resin exhibited nearly a threefold improvement in char yield compared to the char yield from a conventional epoxy resin. After burning, the residue from the composite prepared with the modified epoxy prevented release of free fibers.

Phenolic resins exhibit high char yields, but are not used as matrix resins for high performance composites because they are difficult to process and are brittle. A cyanate modified phenolic resin was developed that exhibited excellent processability. The results of studies to determine the effects of absorbed moisture on composite properties indicated that the moisture resistance of the cyanate phenolic needed to be improved.

The synthesis of higher char polyester matrix resins was also studied and a modified polyester resin was synthesized which exhibited a char yield of about 30 percent compared to less than 10 percent for a conventional polyester resin.

A number of different silicone copolymers were also studied to increase char yield. The approach was to incorporate silicone moieties into polyesters, epoxies, phenolics, and polyimides. Silicone modified polyesters exhibited improved char characteristics, but were difficult to prepare. Silicone modified epoxies exhibited exceptional improvement with anaerobic char yield of up to 50 percent. The anaerobic char yields of silicone polyimide and silicone phenolic ranged between 50 to 60 percent. Additional studies would be needed to identify improved composites processing parameters or to identify modified polymer molecular structures for improved processability.

A program was conducted to evaluate the performance of an ultra-high modulus organic fiber as a reinforcement for composites. The fiber, designated as Fiber D by duPont, has a modulus of 25 million psi and a tensile strength of 456 ksi, respectively. The room temperature compressive strength was only 34 ksi. Exposure to moisture significantly degraded the elevated temperature properties of the composite. Efforts to improve the composite properties by preparing hybrid composites comprised of Fiber D and either graphite fibers and alumina fibers in the epoxy matrix met with limited success. The flexural and compressive strengths of a Fiber D graphite fiber hybrid were significantly lower than those of an all graphite fiber composite.

In-house and contractual studies were performed in an effort to identify hybrid composites which eliminated the release of carbon fibers. The hybrid concept which resulted in the complete retention of carbon fiber was the addition of a particulate boron fiber. Fine boron particles (0.44 mm diameter or less) were dispersed throughout graphite fiber epoxy composite by mixing the powder in the matrix prior to fabricating the composite. The quantity of boron powder was about 6 percent of the composite weight. The addition of boron had little effect on the processing characteristics and mechanical properties of the composites. Composites that were exposed to radiative heat source at 816° C in flowing air exhibited complete fiber retention, whereas composites without the boron filler exhibited poor fiber retention. In addition to preventing the release of free fibers, the boron powder also appears to stabilize the char which forms during burning. This finding suggests that the addition of boron powder to a graphite/epoxy composite would improve its structural integrity retention characteristics in a fire.

Fiber release tests with a laboratory screening test developed at NASA Ames proved that increased resin char yield (ash residue) could significantly reduce carbon fiber release. This provided impetus toward development of higher char yield resin

systems. Polystyrilpyridine (PSP) provided the highest char yield and showed the greater fiber retention, but rated low in mechanical properties and manufacturing ease. Flammability tests showed the higher char yielding resins to be also the least flammable systems. Tests showed a near linear correlation between short beam shear strength and interfacial bond strength. This relationship indicates clearly that the fiber-resin interface adhesion is limiting the strength of the thermally preferable resins. Better higher temperature sizings would be needed for fibers used in these systems.

The Ames' modified carbon fiber manufacturing process resulted in an improved tensile strength for carbon fibers made from polyacrylonitrile (PAN) processed at low temperatures. This result appears to be due to a synergism between an acid pretreatment and a carbon deposition process on carbonization. The mechanisms and properties of the intermediates have been studied to try to improve fiber characteristics further. The surface characteristics of the material used in the carbonization step are different due to the acid processing and this may affect the carbon deposition step.

At the Jet Propulsion Laboratory, several catalysts were proven to be capable of gasifying carbon fibers in air when subjected to a typical fire situation. A combination of calcium acetate and potassium acetate catalyzed the gasification far more than either of the two salts individually. Lithium, when added to calcium, was also found to be synergistic. Tests were conducted to determine the number of electrical short circuits around a composite subjected to a flame and mechanical vibration. The catalytically treated composites gave no shorts. Short beam shear strength tests showed that the mechanical properties of the catalyst treated composites were about 10 percent lower than the untreated composites.

NASA Marshall Space Flight Center has been conducting experimental studies on pyrolytic silicon-carbon-nitrogen fibers which have higher electrical resistance than carbon/graphite fibers. In this program, an amino-silane monomer has been synthesized and converted to a soluble, polymeric silazane resin. Very fine fibers up to 2 feet in length have been drawn from the silazane resin melt. Moisture conditioning during the prepyrolysis step appears to convert the fiber to a moisture-stable, nonmelting material. Subsequent pyrolysis at 1200° C yields a black shiny fiber. In an alternate approach, $Si_XN_YC_Z$ fibers from polycarbosilances or polycarbosilanzane precursors were evaluated. The polysilazane pyrolyzed fibers produced to date are fragile and weak, while the carbonsilane pyrolyzed fibers are satisfactory.

In summary, the program of modifying graphite fibers and developing alternative materials produced several technically viable approaches to minimizing the potential electrical shorting from fire released fiber. The following are some of the more promising approaches:

1. SiC SiO_2 coatings can make fibers nonconductive without significantly affecting the mechanical properties of the fiber or the composite.

2. Boron nitride fibers, which are electrically nonconducting, can have mechanical properties similar to those of carbon fibers.

3. Novel curing agents for epoxy resin increase the char yield of epoxy composites nearly threefold; the residue exhibits excellent structural integrity after burning.

4. Various forms of hybrid construction of composites can reduce or eliminate the release of carbon fibers. The most attractive is the dispersion of fine boron particles in the matrix since it appears to have little effect on the processing or mechanical properties and it improves the retention of structural integrity after a fire.

5. The modified process for making carbon fibers shows promise for a fiber with good mechanical properties and reduced electrical conductivity.

6. Several combinations of catalysts, applied to carbon fibers, will facilitate consumption of fibers in a fire with only modest loss in mechanical properties.

As the risk assessment conducted by NASA progressed, and it became evident that the potential risk is small, the material modification effort was brought to a conclusion. In a few instances, such as the boron nitride fibers, novel curing agents, some hybrid constructions and the process for making carbon fibers, development or evaluation efforts are being continued in other programs because of prospective benefits beyond the fiber release issue. The study results are contained in NASA references 68 through 108.

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15. Supplementary Notes

Reports by NASA, DOT, DOE, DOD, EPA, DOC, DHHS (NIOSH), DOL (OSHA), and FEMA on the national carbon fiber study

16. Abstract

A coordinated federal government action plan was announced in January 1978 to study the potential problems arising from the projected increased use of carbon-fiber composite materials in civilian applications. The primary concern was the electrical hazard associated with carbon fibers released from burning of carbon-fiber composites and disposal of carbon composite waste or worn-out parts. The federal government action plan assigned responsibility for various elements of the study to appropriate federal agencies. This third annual report of the Office of Technology Policy (OSTP) contains the final reports of the NASA, DOT, DOE, DOD, and DOC and the progress reports of the EPA, DHHS (NIOSH), DOL (OSHA), and the FEMA. Also included in this report are the findings of the OSTP, the status of agency responsibilities, and a list of applicable references.

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